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The purpose of this thesis is to investigate the influences of urbanization on long-term streamflow patterns in different physiographic regions of North Carolina. Specifically, I selected, mostly, low-order streams in the three physiographic regions of Mountain, Piedmont, and Coastal Plain. ArcGIS was used to generate watersheds for each of the study sites using Digital Elevation Models downloaded from the North Carolina Floodplain Mapping Program. Streams were chosen for each study area based on the available streamflow data from the US Geological Survey. Impervious surfaces were then extracted from the 2006 National Land Cover Database. Nine metrics were selected to run on each of the stream station chosen using Statistical Analysis System. The metrics used in this study were chosen with the intention of seeing a pattern develop within the counties and across the different physiographic regions. It was expected that changes in long-term streamflow patterns are related to the urbanization process that has occurred in a watershed, and that some metrics of streamflow show urban influences better than others. In other words, not all the streamflow metrics reveal equally the relationships between land use change and streamflow patterns. The metrics used in this study, for the most part, appeared to be effective, especially for the Piedmont sites and to a lesser extent the Coastal Plain and Mountain sites.

INFLUENCES OF URBANIZATION ON LONG-TERM STREAMFLOW PATTERNS IN DIFFERENT PHYSIOGRAPHIC REGIONS OF NORTH CAROLINA

by

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Approved by

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Committee Chair

To Marion who encouraged me and was there every step of the way.

APPROVAL PAGE

This thesis has been approved by the following committee of the faculty of The Graduate School at the University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

Urbanization is a dominant trend that affects the landscape at all levels and is a growing trend throughout the world. As a result of urban development, land is cleared, soils are compacted and graded, and buildings and roadways are constructed. Urban development results in a greater scale of runoff from the new impervious surfaces by limiting infiltration, groundwater recharge, subsurface flow, stormwater storage, and reducing the amount of time the stormwater runoff takes to travel to a stream (Paul and Meyer, 2001; Schueler, 1995; Finkenbine et al., 2000; Poff et al., 2006). The modern urbanized areas are developed with stormwater systems to rapidly removing and diverting the runoff into the local streams. The stream channels are sometimes straightened, deepened, or lined with concrete or rocks to help prevent erosion. Each change allows for larger amounts of water and sediment to move quickly downstream with as little resistance as possible, increasing the “efficiency” of the stream (Booth and Jackson, 1997).

Every watershed responds differently to human interaction or disturbance; some of the measurable degradation can be seen at nearly every level of urban development (Booth et al., 2002). Urbanization can be measured by the amount of the impervious surface it has created (McMahon and Cuffney, 2000; Schueler, 1995). An impervious surface decreases the amount of rain the ground absorbs, and therefore, runoff is increased. Examples of impervious surfaces include roadways, rooftops, driveways, sidewalks, and parking lots. Newly manicured lawns, unpaved roads, and trails consisting of gravel or compacted dirt are considered impervious surfaces, because they are so compacted and water cannot be easily absorbed.

Streams respond differently to changes in the watershed where they are located. Spatial patterns of how the impervious area is designed and developed, and how the land cover is modified plays a crucial role in how watersheds respond to impervious surfaces (Alberti et al., 2003). Areas that have sand and gravel have been shown to have high infiltration and low runoff rates, compared to areas that have underlying clay, which tend to have low infiltration and high runoff (USDA-SCS, 1986). Also, Bledsoe and Watson (2001) suggest that smaller stream channels have the ability to absorb water faster and show more erosion response to urbanization.

The focus of this research has one main objective: To use a variety of streamflow metrics to compare the influences of urbanization to rural streams in the different physiographic regions of North Carolina using long-term streamflow data. It is expected that changes in the long-term streamflow patterns are related to the urbanization process that has occurred in a watershed, and that some metrics of streamflow show the urban influences better than others. In other words not all the streamflow metrics reveal equally the relationships between land use changes and streamflow patterns.

CHAPTER II

LITERATURE REVIEW

There are several aspects of urbanization that may impact streams. These factors include, but are not limited to, the increase in impervious surfaces, sediment supply during the construction phase, the removal of vegetation, straighten of stream channels, and the creation of detention ponds. Streams response may vary between different physiographic regions to urbanization.

Urban areas and urbanization

The term “urban” is used loosely by scientists (McIntyre et al., 2000) and may have different meanings depending on the study context. Social scientists use the term “urban” in reference to areas with high human population density (McIntyre et al., 2000). Ecologists use “urban” in more of a broad sense, referring to areas that are under human influence (McIntyre et al., 2000).

Quantifying an urban or rural landscape varies per study and scientist. Neller (1988) classifies a rural landscape as having less than 3% of its watershed area covered by impervious surfaces. Neller (1988) went on to describe areas that are in the process of being converted from rural to an urbanized landscape as having between 3-10% covered by impervious surfaces. Areas that have been completely transformed into an urbanized landscape are described as having more than 10% impervious surfaces (May et al., 2002). In comparison, Finkenbine et al. (2000) describes a rural landscape as having less than or equal to 7% percent Total Impervious Area (TIA), and urbanization greater than or equal to 15% TIA.

Urbanization may also be measured based on the effects it has on streams. Henshaw and Booth (2000) found that instability of a stream could be detected at any level of urban development. Other studies have found that the threshold of impervious surface effect on streams can be seen at 10-20% (Booth and Jackson, 1997; Schueler, 1995; Bledsoe and Watson, 2001). The measurable effects can be equated to the decline in aquatic life, habitat, and vegetation throughout a stream’s ecosystem (Booth and Jackson, 1997). A change in a stream’s flow can cause significant damage to aquatic life and riparian ecosystems (Poff et al., 2006). Additionally, it was found that streams in less developed areas were more stable on average compared to streams with more developed watersheds (Henshaw and Booth, 2000).

Effects of urbanization on streamflow regime

Urbanization affects the water levels in a stream, as well as many other facets of fluvial processes. Sediment supply, the quantity of water that ultimately makes it to the stream, and erosion or deposition of sediments in the stream are all examples of the hydrologic processes that are altered due to increased urbanization.

Hydrologic processes and streamflow regime are directly affected by urbanization. The highs and lows of streamflow can be affected by an impervious area and vegetation or lack of vegetation, all of which are a direct result of human urbanization.

Studies have shown that over time, the channel width and depth of a stream adjusts in response to increases or decreases in sediment supply and bankfull discharge eroding the channel banks (Paul and Meyer, 2001; Finkenbine et al., 2000; Arnold et al., 1982; Hammer, 1972). Bankfull discharge is the maximum amount of water a channel can move without overflowing into the floodplain. In eastern U.S. streams where the human impact has not reached the extent displayed in urbanized areas, bankfull discharge occurs roughly one to two times per year (Leopold, 1994). Streams affected by urban development exhibit bankfull discharge more frequently, at least three (Klein, 1979) to five times per year (Booth, 1991).

Sediment supply to streams is affected by urbanization. In urban areas, natural channel densities decrease dramatically because small streams are filled in, paved over or piped (Paul and Meyer, 2001). The beginning of development exposes soils, making them easily erodible. Also, the removal of riparian vegetation leads to higher rates of runoff and erosion (Simon et al., 2004*).* The eroded soil fills the stream channels, leading to a decrease in channel size. The decreased channel size and increased sediment load turns streams that were once meandering into a braided (Arnold et al., 1982). Also, a decreased channel size and increase in sediment load tends to lead to more floods and larger flooding events (Paul and Meyer, 2001).

Once development is complete, the stream's supply of sediment is reduced and the amount of impervious surface is increased. Due to the urbanization, the increased impervious surfaces yield higher runoff, causing stream channels to erode, deepen, and widen in order to contain the increase in flow (Paul and Meyer, 2001; Arnold et al., 1982). This increased flow tends to yield less fine-grained sediment and more coarse sand as a result of a change in sediment sources and water velocity (Finkenbine et al., 2000; Pizzuto et al., 2000). It was discovered that increases in peak discharge for low-density developments were more significant when forests were cleared to create lawns, as opposed to small increases in impervious areas of low-density development (Booth et al., 2002). Hydrologic analyses have suggested that maintaining forest cover is more important than limiting impervious areas, at least in rural residential areas (Booth et al., 2002).

Streams in Different Physiographic Regions

Mountain Streams

Most of the streams in the United States represent low-order streams, such as forth-order and smaller. These streams are the most likely to exhibit changes caused by the surrounding land-use (Allan, 2004; Knox, 1977; Gomi et al., 2002). Mountain streams are responsible for draining an estimated 20% of the land around the world and contribute almost 50% of all the sediment supply that eventually ends up in the ocean (Milliman and Syvitski, 1992). They supply nutrients to lakes, rivers, and ultimately, oceans and estuaries (Wohl, 2006).

Many regard mountain streams as pristine and untouched by humans, but studies have shown this thought is untrue. In fact, very few mountain regions have streams that have not been moderately affected by changing land use (Wohl, 2006). Mountain streams are easy and important sources of water and are easily altered to allow for storage, diversion, and the generation of power (Wohl, 2006).

Rose and Peter (2001) studied the association between streams' baseflow recessions located in urban areas with those in less developed areas. By calculating runoff coefficients, they were able to group streams geographically. As the elevation and relief of a watershed decreased, the runoff coefficient generally decreased. In addition, historical streamflow data indicated that runoff decreased with elevation and relief (Rose and Peter, 2001). They stated that by grouping the runoff coefficient there is no indication that the annual runoff of streams in the various regions was influenced by urbanization, but that different physiographic regions had a role in stream's behavior.

Piedmont Streams

Harman et al. (1999) studied streams' dimensions in reference to bankfull discharge and compared them to the drainage area of the watershed in the Piedmont of North Carolina. The results indicated that the bankfull stage occurs at an average frequency of 1.4 years (Harman et al., 1999).

Doll et al. (2002) compared bankfull dimension to discharge of streams located in an urban setting to streams in a rural setting throughout the Piedmont of North Carolina. They found that urban streams have enlarged bankfull dimension compared to rural streams, and that bankfull stages occur at an average frequency of 1.3 years, which is a little more frequent than the 1.5 years usually predicted for rural streams ranging from 1.09 to 1.8. As urbanization increased, the bankfull average width and depth tended to increase (Doll et al., 2002).

Turner-Gillespie et al. (2003) compared flooding along Little Sugar Creek, in Charlotte, to the surrounding area, and with reference to urbanization and the underlying geology. Their study concluded that abrupt changes in morphology occurred near the contact between igneous and metamorphic rock types. Along Briar Creek, they found that peak flood response was extremely sensitive to changes in urbanization (Turner-Gillespie et al., 2003).

Coastal Streams

Doll et al. (2003) studied streams in the rural Coastal region of North Carolina in an effort to identify bankfull dimension and discharge. They compared bankfill stream dimension to the watershed drainage area and found that bankfull discharge occurs on an average frequency of 1.12 years. The results indicated that as the watershed drainage area increased, the stream's channel increased in size, too (Doll et al., 2003).

Hardison et al. (2009) studied low-order stream channel formation and hydrology in comparison to vegetation in six catchments. Each catchment was located in varying degrees of urbanization based on TIA percent in the inner Coastal Plain. Hardison et al (2009) concluded that riparian vegetation and other biological aspects in an urban setting were unlikely to be restored to the pre-urbanized state due to the loss of floodplain and the change in environment.

O'Driscoll et al. (2009) examined small watersheds located in the southeast Coastal Plain of North Carolina. Their objective was to associate a stream's response to impervious surfaces in an urbanized setting in association with stormwater runoff, bankfull discharge, woody debris, and sediment size. They found that a stream's dimensions enlarged downstream of stormwater outfalls compared to upstream. Woody debris was present in all of the rural streams, but was found in only seven out of twenty urban streams (O'Driscoll et al., 2009). Urban streams were found to have larger sized gravel and less fine grained material compared to rural streams (O'Driscoll et al., 2009).

Measurement of Streamflow Patterns

Streamflow metrics or hydrologic indicators are indices that describe streamflow patterns, such as mean annual flow, daily, seasonal, and annual flow variability, standard deviation, flow duration percentiles, timing of extreme flows, intermittent flows, frequency, duration of floods, and rates of change (Poff et al., 1997). The purpose of these indicators is to evaluate the overall health of a stream or river and to study the changes in a stream caused by alterations within its watershed (Gao et al., 2009). Streamflow metrics were created to illustrate different aspects of an area, to study the different forms of human disturbance, and attempt to characterize different components of streamflow with various metrics (Olden and Poff, 2003).

Olden and Poff (2003) explored some of the different metrics to help determine which were most important based on the focus of a subject study and minimize overlap. Scientists have approached the classification of streamflow in many different ways. Olden and Poff (2003) described early studies in which they focused on one metric at a time. Examples included: variation in mean daily flow, slopes of flood-frequency curves, seasonal distributions of monthly flows, and flow and flood frequency duration curves. More recent studies have focused on combinations of multiple metrics in a study, rather than individual metrics (*Olden and Poff, 2003*).

The use of individual, rather than collective, streamflow metrics is susceptible to criticism as overly simplistic and sometimes lacking in biological relevance (*Olden and Poff, 2003*). In recent years, there has been an explosion in literature of more comprehensive indices of streamflow metrics (Olden and Poff, 2003). With so many types of metrics now available, researchers are forced to choose from a long list of inter-related and sometimes overlapping indices. For example, Richter et al. (1996) developed Indicators of Hydrologic Alteration (IHA), which includes 33 hydrologic standards, to help characterize a stream based on human modifications of flow. Of the 33 metrics, there are several that are inter-correlated (Olden and Poff, 2003).

Reducing the amount of redundant indices analyzed will result in a small and more manageable group and reduces the time and resources required to characterize a stream (Olden and Poff, 2003). Failure to focus and consolidate indices used in a study could result in a failure to identify important variables and possibly bias in the resulting streamflow model (Olden and Poff, 2003). They pointed out that some redundancy is good and could detect different streamflow patterns, but it must be recognized and kept in perspective.

Konrad and Booth (2002) studied four metrics in association with urban development and land use changes. The metrics included: annual mean discharge, annual maximum discharge, annual 7-day low flow, and fraction of year that annual mean discharge is exceeded. The annual mean discharge, which is not strongly altered by urban development, served as a basis for normalizing streamflow patterns in comparisons among streams. Annual mean discharges were used for analysis of long-term dynamics, as well as, downstream propagation of urban influences. They found that maximum discharge is difficult to measure when flood peaks are brief and simultaneous in small groups of urban streams. The fraction of a year that annual mean discharges were exceeded is a better indicator of the effect of land use changes on ecological environments (Konrad and Booth, 2002). Both annual mean discharge and 7-day low flow had mixed results in comparing urban and rural streams.

Part of Olden and Poff's (2003) research was to determine if streamflow metrics could be linked geographically to a range of climates and geology. They studied a variety of common stream types throughout the world and found the streamflow metrics varied a significant amount among the different stream types (Olden and Poff, 2003). The results indicated that individual metrics, in general, were stream-type specific with strong patterns of variance (Olden and Poff, 2003).They suggested that while some streamflow metrics could be transferred between certain stream types, they recommended that metrics reflect the climate and characteristics of the study area. Olden and Poff (2003) also concluded that more research needs to be done to address whether metrics can be compared across varying physiographic regions.

CHAPTER III

RESEARCH METHODS

Geology, topography, climate and associated soil type play an important role in streamflow dynamics. As described in this chapter, a strong understanding of the physical setting of a watershed and its' streams is an important first step in understanding changes associated with urbanization. The nature of the physiographic regions of North Carolina is first summarized, followed by the selection and description of the specific sites that form the basis of this study. Data compiled for the study sites are then presented and evaluated.

Region

North Carolina is located in the mid-Atlantic of the United States and includes 100 counties. Three distinct physiographic regions are recognized based on the underlying geology and topography: the Mountains/Foothills in the western portion of the state, the Piedmont located in the central, and the Coastal Plain in the east. North Carolina has one of the greatest elevation differences among the states east of the Mississippi River, ranging from sea level along the Atlantic Ocean in the Coastal Plain to 2,037 meters (m) in the Mountains.

North Carolina has seventeen major watersheds, several of which are completely contained within the state’s boundary. Based on drainage divided, rivers and streams in North Carolina can be divided into two groups: those that flow into the Atlantic Ocean and those that flow into the Mississippi River, with the latter located in the western part of the Mountains. The major rivers that flow into the Atlantic include: the Roanoke, Tar, Neuse, Cape Fear, Yadkin, and Catawba. Rivers that flow west into the Mississippi drainage network include French Broad and the Tennessee.

North Carolina has a humid climate with four distinct seasons. The difference in latitude will alter the climate, and the Gulf Stream can affect the temperatures, particularly along the Coastal area. North Carolina winters are usually mild and short; summers tend to be very sultry; and the spring and fall have refreshing periods of transition with milder temperatures.

North Carolina does not have a distinct wet or dry season, but the summers tend to have the greatest amount of precipitation, the majority of which come from passing showers and thunderstorms (State Climate Office of North Carolina, 2011). Autumn is the driest season, while winter and spring are characterized by an increase in precipitation (State Climate Office of North Carolina, 2011). The eastern portion of the state gets more frequent storms compared to the rest of the state (Table 1 - State Climate Office of North Carolina, 2011).

Table 1. Average Annual Rainfall across the region of North Carolina.

County	Region	Average Annual Rainfall (in)
Ashville	Mountains	45.5
Charlotte	Piedmont	43.5
Guilford	Piedmont	44.6
Durham	Fall Line/Piedmont	48
Wake	Fall Line/Piedmont	45.4
Cumberland	Coastal	46.9

Due to hurricanes forming in the Atlantic Ocean in the late summer and early fall, the coast is vulnerable to high winds and flooding. Constant development and no elevation relief along the coast lend very little protection from storm surges that occur. In the Mountains, hurricanes and strong storms can cause flooding and landslides. The Piedmont also feels the effects of hurricanes in the form of high winds and flooding.

North Carolina land use varies by region with elevation influencing agriculture practices. North Carolina is the leading producer of hogs, turkeys, and chickens, with most operations located in the Piedmont and Coastal Plain. The North Carolina Mountains offer the perfect climate for Christmas tree and apple farming.

U.S. Census statistics show that North Carolina had the ninth highest growth rate among all the states between 2000 and 2005 (Stuart, 2006). In 2010, the North Carolina population was 9.5 million, consisting of 195.8 people per square mile, an 18.5% increase in growth from the year 2000 (US Census Bureau, 2011). By 2004, over two-thirds of North Carolina was considered an urban area by the federal government. The Census Bureau defines an "urban area" as an area that is comprised of one or more counties that contain a city greater than or equal to 50,000 people (Stuart, 2006).

The U.S. Census Bureau has projected that North Carolina will grow to 12.2 million by 2030 (Stuart, 2006). The growth is expected to be concentrated in the metropolitan areas of the Piedmont region (30%), mostly in Mecklenburg County (Charlotte metro area) and Wake County (Raleigh).

Mountains/Foothills

The Appalachian Mountains extend from Alabama to Newfoundland. Sub-ranges of the chain include: the Great Smoky Mountains, Blue Ridge Mountains, Great Balsam Mountains, and Black Mountains. In North Carolina, the Mountains are at their highest with roughly 43 peaks above 1,800 m; Mt Mitchell being the highest elevation at 2,037 m and the highest peak east of Rocky Mountains. The Mountains have been heavily folded and faulted from having undergone up to four tectonic orogenies (Stewart and Roberson, 2007). The mountain range exhibits the oldest rocks in North Carolina, some dating back to 1.8 billion years and is estimated to have once been as high as the Himalayans. Today's Mountains are the weathered remains of the last orogeny, the Alleghanian, which began about 330 million years ago. The remains of the Mountains have the greatest elevation variation in each of the three regions. The steep topography is a factor in stream morphology and has a higher rate of runoff. Soils in the Mountains are generally thin, organic-rich and gray-black in color.

Spring has a variety of weather that can range from snow to temperatures in the 90’s, but temperatures are usually mild and the season fairly wet. Summer temperatures typically are in the mid 80’s, occasionally reaching into the 90’s. In the Mountains, fall is the driest season and offers cooler temperatures ranging from 50’s to 70’s. Tropical systems are possible during this time of year with heavy rains and high winds. Winter in the Mountains is considered the wet season and typically has significant snowfall. The daytime high temperatures average in the upper 30’s to low 50’s, and nights can fall into the low teens. Snowfall in the Mountains can range from 36-51 centimeters (cm) per year, increasing at higher elevations. Mt Mitchell received 127 cm of snowfall during the Great Blizzard of 1993.

Agricultural production is small due to the rugged topography and a cooler climate. With the topography and cooler climates, specialized agriculture thrives on the hill slopes and valleys of the Mountains such as apples, Christmas trees, and other fruits. Logging has become part of the local economy, with most of the area being forested at one time. Tourism and associated urbanization has become a major part of the local economy with skiing in the winter; rafting, fishing, and hiking in the summer; and leaf viewing in the fall. The human influence in the Mountains tends to be localized, with 50% of the watershed areas remaining forested (Harman et al., 2000).

Piedmont

The Piedmont encompasses a large area that extends south to Alabama and runs north to southeastern Pennsylvania. The Piedmont is primarily underlain by metamorphosed, Late Proterozoic (approximately 800 to 543 million years) to Paleozoic Era rocks (550 to 200 million years). The typical rock types include, but are not limited to, granite, gneiss, schist, and slate. America's first gold and gem mines were located in the Piedmont. The central portion of the Piedmont is characterized by un-metamorphosed, sedimentary rocks associated with former rift valley of the Triassic Period (200 to 180 million years). This area is primarily underlain by mudstone, traprock, and conglomerates.

The topography of the Piedmont is characterized by gently rolling hills that slope eastward from an elevation of approximately 457 m at the base of the Blue Ridge escarpment and to approximately 61 m at the "fall line," which separates the eastern Coastal Plain from the Piedmont. Steeper hills in the Piedmont generally reflect the presence of more resistant rock types, in comparison to the surrounding area. The steeper hills can be found in the Uwharrie Range and Kings Mountain Range, located in Randolph, Cleveland, and Gaston Counties.

In the Piedmont, soils are generally Ultisols with a light upper layer and reddish subsoil. Most of the Piedmont soils are red in color due to high levels of iron oxides. Localized areas are characterized by very compact, grayish clay.

The Piedmont has experienced a rapid growth in the last few decades, resulting in the largest population in the state. Due to the rapid population growth, many farms and much of the rural countryside are being replaced by shopping centers, homes, and offices. The remaining agriculture and livestock operations include: peaches, grapes, cotton, tobacco, turf for manicured lawns, hay, chickens, cattle, and pigs.

The temperature in the Piedmont during the winter months is highly variable, and can average in the mid 60's during the daytime and drop below freezing at night. The Piedmont averages 8-13 cm of snowfall annually, with 15-20 cm in the Raleigh-Durham area. The region receives sleet and freezing rain during the winter months. Annual precipitation ranges from 112 to 122 cm. The Charlotte area gets 110.5 cm on average of precipitation per year.

Coastal Plain

The eastern Coastal Plain covers the largest area of North Carolina and consists of Tertiary to Cretaceous-age sediments and sedimentary rocks onto the Piedmont. The Coastal Plain extends north from New Jersey to south Florida and inland up to 200 kilometers or more (e.g., Raleigh, North Carolina). The Coastal region in North Carolina can be divided into two sections: the tidewater area and the inland or "immediate" coast. The tidewater area is generally flat, swampy, and lies closest to the ocean. The immediate coast is gently rolling and well drained.

The Coastal area is comprised of predominantly marine sedimentary rock that dates from the Quaternary Period (less than 2 million years) back to the Tertiary Period (2 to 65 million years). In the southeast corner of the coastal area, older sediment dates back to the Cretaceous Period age (140 to 65 million years). Small occurrences of limestone have been encountered and are mined in this area. The Coastal Plain sediments and sedimentary rock dip gently to the east, with an elevation of approximately 61 m near the fall line and an average of less than 15 m over the tidewater area. There are some sand dunes in the southeastern corner, called Sandhills, that have a high point of 225 m; but generally speaking, there is very little elevation change over this area.

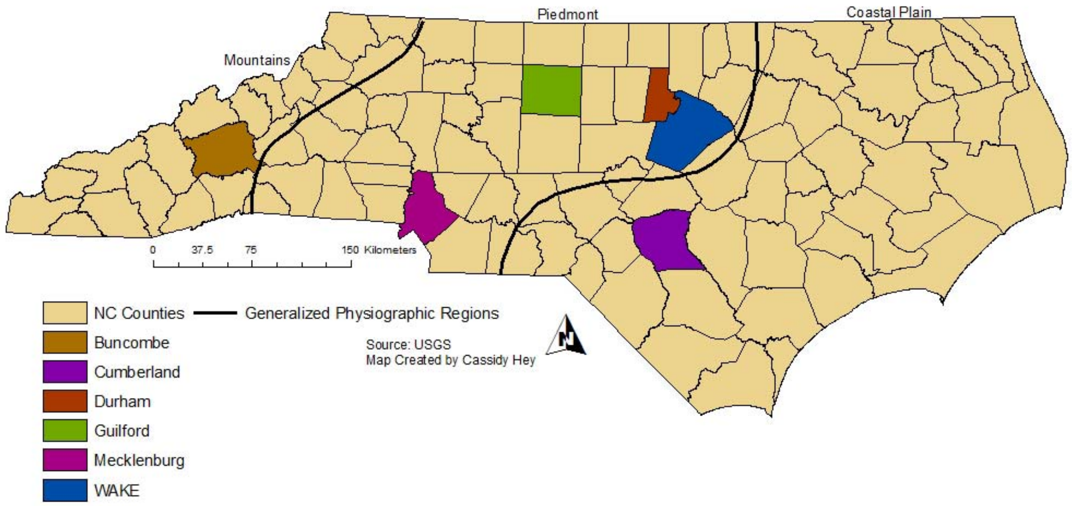
The soil in the Coastal Plain is comprised predominantly of very permeable, sandy soils with localized, low-permeability clay sequences. The Coastal Plain soils can vary tremendously and reflect how the parent material was deposited when the region was once an ocean. In both sections of the Coastal Plain, the soil consists of soft sediment with little to no underlying bedrock near the surface.

The land use is reflective of the soil types and how the soils drain in the Coastal Plain. With deep, rich soils, abundant flat land, and longer growing seasons, the land is ideal for agriculture and farming, which are the major industries in this area. The two major crops include tobacco and cotton; for farming, hogs and turkeys are the two major animals raised. There are a few large towns and cities, but most of the Coastal Plain is considered rural. Tourism is a large part of the local economy, as tourists flock to the beaches during the summer time. Along the coast, the summer months are usually cooler than other locations within North Carolina due to the Coastal winds and the relative humidity averaging about 75%. The annual precipitation is about 112 to 142 cm. Along the Coastal Plain; the average snowfall amount is minimal compared to more inland areas.

Study Sites

For this research, the study sites are located in the following counties: Buncombe County (Mountains); Mecklenburg, Guilford, Durham, and Wake Counties (Piedmont); and Cumberland County (Coastal Plain) (Figure 1).

Figure 1. Study Areas



Three criteria were initially used to select study sites for inclusion in this research project: 1) Presence of United States Geological Survey (USGS) stream stations for low-order streams, 2) Presence of streams located in both rural and urban areas in each of North Carolina's three physiographic regions, and 3) Availability of long-term daily mean flow stream data. For selection, a station required at least 10 years of consecutive data in order to classify the results that represent the effects urbanization has on a stream. Streams with any size or type of dam located within the watershed were excluded. Selecting streams proved to be problematic, since there are over five thousand dams in North Carolina.

The selection of study locations on streams for each region was based on certain criteria. Each region needed a stream located in an urban and rural setting. The urban and rural streams had to be in close proximity to each other in order to minimize factors that might be specific to one stream station, including disturbances, geology, topography, and soil type. When considering streams for a rural setting, streams that flowed through an urban area were not used. Rural streams should have very slight influences from urbanization.

Selecting low-order streams for classification was done for several reasons. First, the small size of the watershed helped to control the amount of disturbance within the watershed boundary. Second, low-order streams were considered the most sensitive to changes to the surrounding landscape (Church, 1992), and were likely to show the changes in the land use (Allan, 2004). Third, this helped to reduce the influences of any structures or devices that could influence streamflow in the watershed, such as diversion structures or dams (Poff et al., 2006).

Utilizing the above requirements, the initial data processing yielded only seventeen possible stations. Out of these possible stations, the Mountains and Coastal areas did not have any urban stations. As for the Piedmont, Charlotte area in particular, both urban and rural stations were available. After the first attempt at processing, it became evident that the parameters for this study needed to be widened. During the second attempt at processing, the parameter for the total consecutive years was changed and lowered to five consecutive years. The result was a greater number of possible stations, totaling 141. Once watersheds were generated, the numbers of stations were reduced due to dams. Out of the 141 possible stations, there were still no urban stations for the mountain and Coastal areas. In order to get an accurate conclusion from the streamflow metrics in each region, the decision was made that the streamflow data needed to be greater than five years for an urban station in the Mountains and Coastal area due to the limited station possibilities. Additional parameters were changed the total drainage area for a stream station was increased, but limited to less than 1,000 square kilometers (km^2); watersheds were no longer omitted due to dams; counties were added mainly to the Piedmont area as a backup; and 5-10% impervious surface was used for a threshold between urban and rural. Hollis (1975) expressed that at low levels of impervious surface urbanization can be seen in streams. This criterion of 5-10% (Hollis, 1975) minimum impervious surface was used, for the Mountain and Coastal areas, because they are not as populated and are not as urbanized as the counties in the Piedmont. This characteristic resulted in seventeen stations (Table 2).

Table 2. Stream stations results.

Site Number	County	Region	Urban or Rural	Drainage Area (km^2)	Stream Name
0344894205	Buncombe	Mountains	Rural	37.50	North Fork Swannanoa
03450000	Buncombe	Mountains	Rural	14.17	Beetree Creek
03451000	Buncombe	Mountains	Urban	336.52	Swannanoa River
02104387	Cumberland	Coastal	Urban	7.17	Buckhead Creek
02103000	Cumberland	Coastal	Rural	892.61	Little River
0214657975	Mecklenburg	Piedmont	Rural	21.70	Irvins Creek
02146409	Mecklenburg	Piedmont	Urban	30.35	Little Sugar Creek
0214627970	Mecklenburg	Piedmont	Urban	23.51	Stewart Creek
02093800	Guilford	Piedmont	Rural	53.38	Reedy Fork
02094659	Guilford	Piedmont	Urban	19.09	South Buffalo Creek
02095181	Guilford	Piedmont	Urban	24.66	North Buffalo Creek
0208735012	Wake	Piedmont	Urban	3.06	Rocky Branch Creek
0208732885	Wake	Piedmont	Urban	17.66	March Creek
0209782609	Wake	Piedmont	Rural	31.12	White Oak Creek
0209741955	Durham	Piedmont	Urban	54.57	Northeast Creek
0208524090	Durham	Piedmont	Rural	20.80	Mountain Creek

Data Quality

The process of generating useful data for some of the stream stations proved to be difficult. Some of the streams appeared to be disconnected in several sections along their course through the watershed; thus resulting in watersheds that appeared smaller than they actually were. The broken streams may be attributed to the topographic relief, because most of the counties where this occurred were Coastal area counties. The software used may have been unable to identify individual streams with such little topography relief. This was the case for one stations in Cumberland County. After several attempts, the watershed had to be drawn by hand to closely match the watershed size found on the USGS web site.

Another issue was some of the stream stations did not have uniform data length. Either the station stopped gathering data early or there are gaps of a day to a few years in the data length. A possible reason that the stations stopped gathering data early was the lack of funding for the site. An example of a station that stopped gathering data early and had gaps was located in Cumberland County (02104387 – Buckhead Creek). Buckhead Creek station started gathering data in 1976 and stopped in 1992.

Gaps were found in most of the streams' stations data. A portion of the gaps only lasted a day, while others lasted years. Some of the gaps could be worked around, so there was at least a ten-year stretch of data with no gaps. The Cumberland County urban station (02104387) has so many gaps making it hard to draw any type of conclusion for the Coastal Plain area.

Mountains Study Sites

Buncombe County

Buncombe County is located in the south central portion of the Mountains of North Carolina (Figure 2). Three USGS stations in Buncombe County were selected; one urban station and two rural. Each station was chosen based on the percent of impervious surfaces in each area of the stream's watershed. The stations lie on the divide that eventually flows into the Mississippi River, instead of the Atlantic Ocean, via the French Broad watershed.

Figure 2. Buncombe County: Three stream stations are located in North Fork Swannanoa (0344894205 - Rural), Beetree Creek (03450000 – Rural), and Swannanoa River (03451000 – Urban), all in the French Broad watershed.

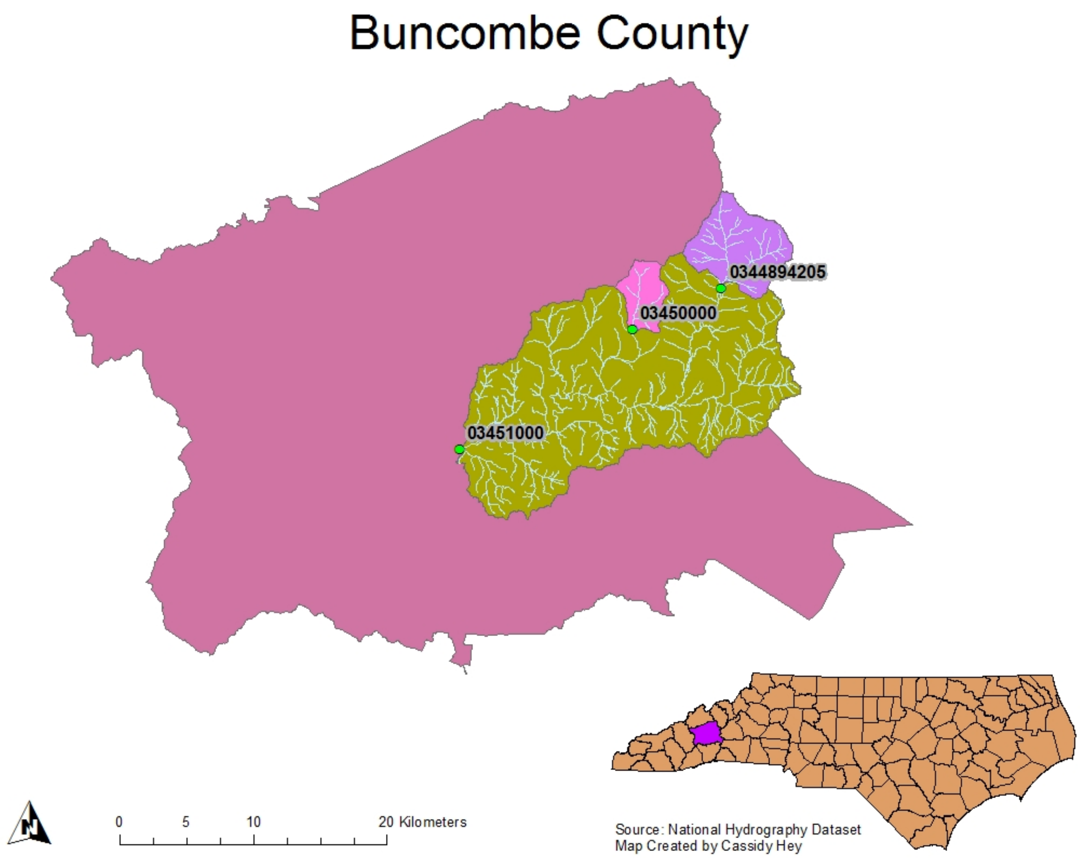


Table 3 (below) lists and describes the stream stations for Buncombe County. North Fork Swannanoa stream station has a watershed of 37.5 km^2 and is considered rural, with only 0.84 % of its watershed covered with impervious surfaces. The length of data is 22 years with a gap on April 5, 2011. It was decided to end the data on April 4, 2011, so there would be no gaps in the data.

Beetree Creek, with a watershed size of 14.17 km^2, is also considered rural with 0.49 % of its watershed covered with impervious surfaces. The Beetree Creek station started recording data in 1926 and continues today. Between October 1975 and August 1985, there are several large gaps, some of which span years. A data gap beginning on April 5, 2011 was used to set an end date of April 4, 2011 (same as above).

The Swannanoa River has the largest watershed area at 336.52 km^2 and an impervious surface of 13.31 %. The wateryears for this station started in 1934 and continues to present day. The station actually began to gather data in 1920, but there was a signification gap of several years from, 1926 to 1934 where no data was recorded. Due to the gap in the data, the start date was June 1, 1934.

Table 3. Buncombe County urban and rural stream stations.

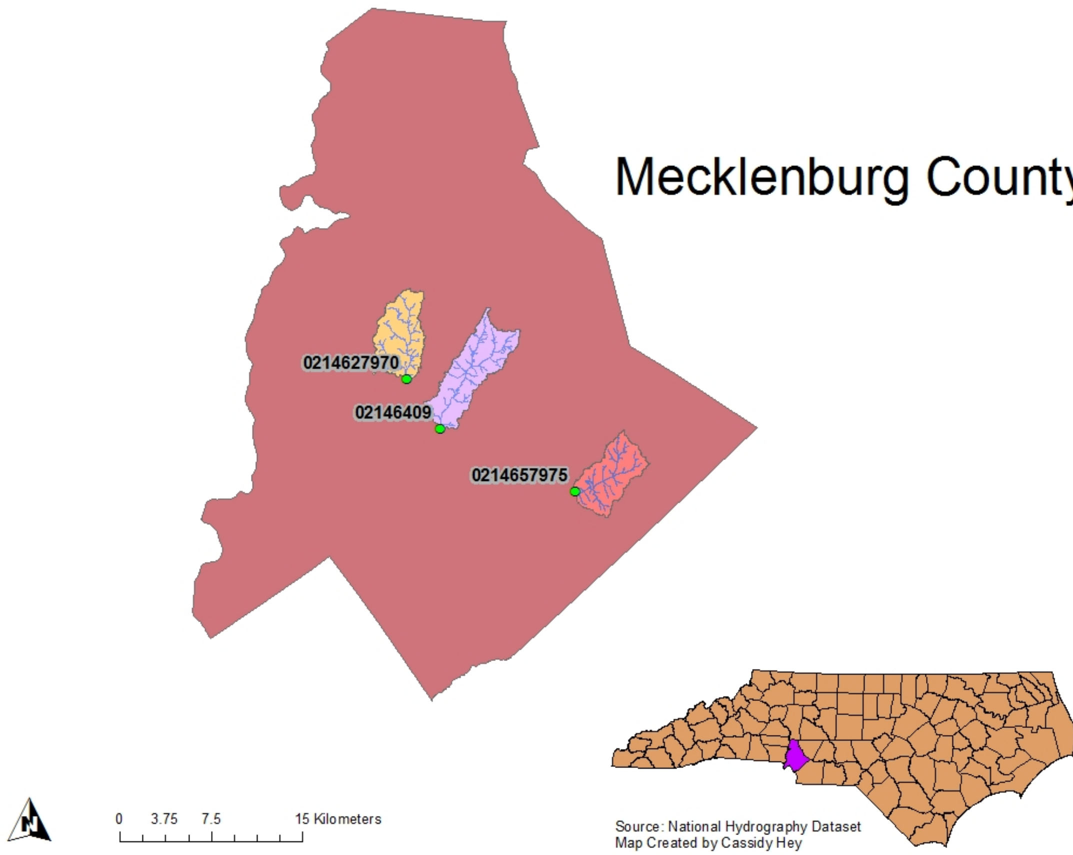
Site Number	Urban or Rural	% Impervious Area	Drainage Area (km2)	Data Record Available	Stream Name
0344894205	Rural	0.84	37.5	2-1-1989—Present	North Fork Swannanoa
03450000	Rural	0.49	14.17	3-1-1926—Present	Beetree Creek
03451000	Urban	13.31	336.52	10-1-1920--Present	Swannanoa River

Piedmont Study Sites

Mecklenburg County

The Piedmont has the greatest number of stream stations and associated streamflow data because of the concentration of population and larger cities. Mecklenburg County is home to Charlotte, the largest city in North Carolina. The county is located in the south central bottom portion of the Piedmont and has three stations (1 rural and 2 urban). All stations are part of the Catawba watershed that ultimately drains into the Atlantic Ocean (Figure 3).

Figure 3. Mecklenburg County: Three stream stations are located along Irvins Creek (0214657975 - Rural), Little Sugar Creek (02146409 - Rural), and Stewart Creek (0214627970 - Urban), all in the Catawba watershed.



The watersheds for Mecklenburg County range in size from 18.28 km^2 to 69.33 km^2 (Table 4). The rural watershed, Irvins Creek (0214657975), has a watershed size of 21.7 km^2. The percent impervious surface is 36.56 %. If this station was in the Mountains or Coastal area, it would be considered urban. For Mecklenburg County, however, this was one of the less urbanized stations that met the study site selection requirements. There was one small data gap when the station first started to gather information. To resolve this, the wateryear was adjusted accordingly.

The two urban stations included Little Sugar Creek at Medical Center Drive (02146409) and Stewart Creek at State Street (0214627970). Little Sugar Creek has the largest watershed size in Mecklenburg County, 30.25 km^2, and has the greatest amount of impervious area as well, at 92.26 %. The wateryears span for seventeen years with no gaps, starting in 1994 to present.

The Stewart Creek station has an eleven year span, starting in 2000 to present, also with no gap in the wateryears. The drainage area is the smaller of the two urban watersheds with 23.51 km^2 and 77.03 % of impervious surface.

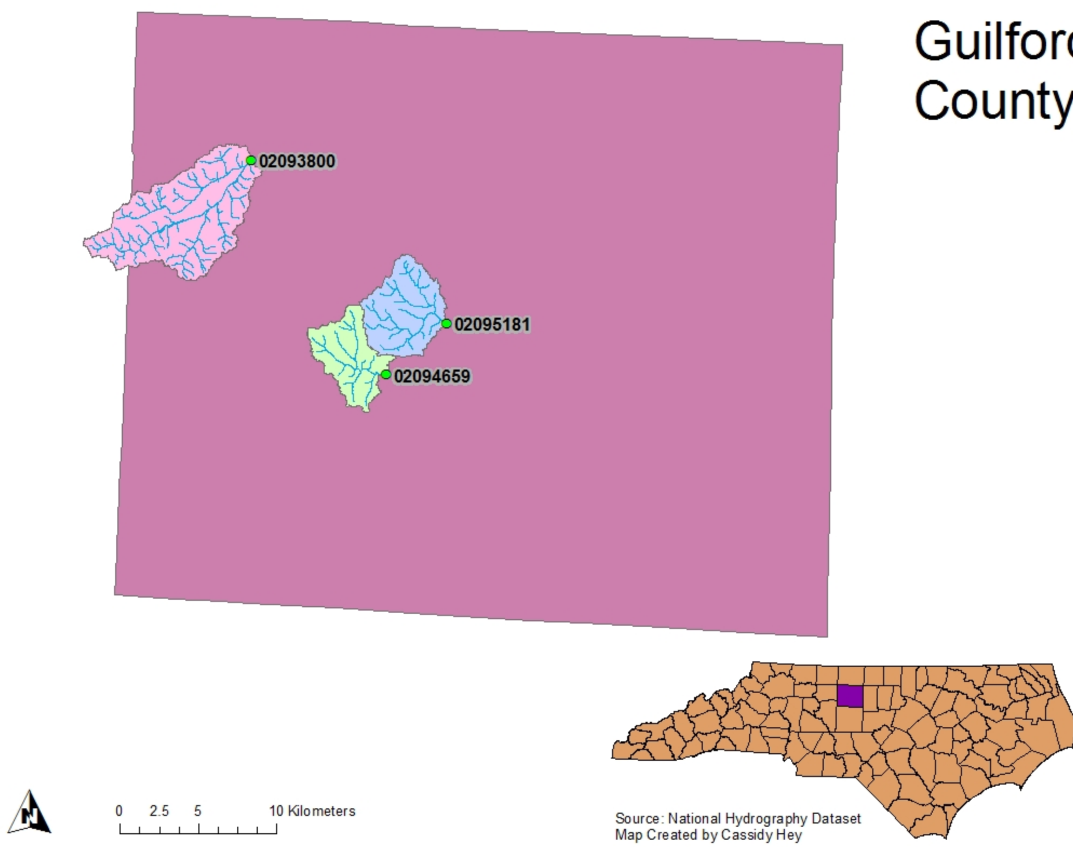
Table 4. Mecklenburg County urban and rural streams stations.

Site Number	Urban or Rural	% Impervious Area	Drainage Area (km2)	Data Record Available	Stream Name
0214657975	Rural	36.56	21.7	5-18-1999—Present	Irvins Creek
02146409	Urban	92.26	30.35	10-1-1994—Present	Little Sugar Creek
0214627970	Urban	77.03	23.51	6-1-2000—Present	Stewart Creek

Guilford County

Guilford County is located in the northern central part of the Piedmont. Three stream stations were selected for evaluation, all located in the Cape Fear watershed that flows into the Atlantic Ocean (Figure 4). Guilford County is not as populated as Mecklenburg County, but is still one of the most populated counties in the Piedmont area.

Figure 4. Guilford County: Three stream stations are located along Reedy Fork (02093800 - Rural), South Buffalo Creek (02094659 - Urban), and North Buffalo Creek (02095181 - Urban), all in the Cape Fear watershed.



Reedy Fork (02093800) near Oak Ridge is the only rural station for Guilford County. The watershed for this station is the largest out of the rest of the stations with an area of 53.83 km^2, but has the smallest amount of impervious surface, 13.61 % (Table 5). The data record length is 56 years with no gaps, beginning in 1955 to present. This is the longest data span for this county.

The two urban stream stations include South Buffalo Creek (02094659) near Pomona and North Buffalo Creek (02095181) at Westover Terrace. South Buffalo Creek watershed is 19.09 km^2 in size and has 85.18 % impervious surface, while North Buffalo Creek has a 24.66 km^2 watershed size and 81.73 % impervious surface. Both of the stations have 12 years of data starting in 1999, but North Buffalo Creek had a small gap in data that required a slight adjustment of the end date.

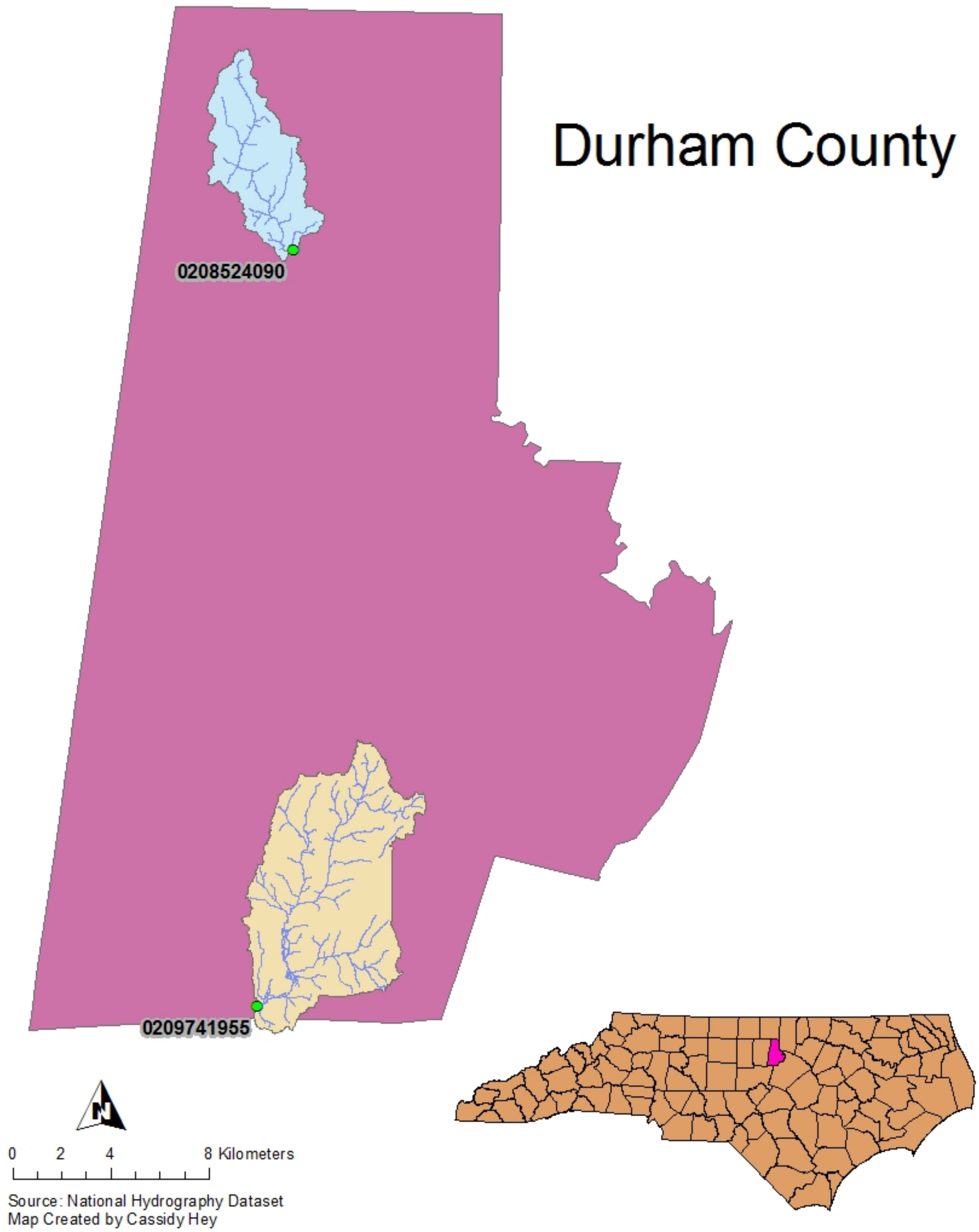
Table 5. Guilford County urban and rural stream stations.

Site Number	Urban or Rural	% Impervious Area	Drainage Area (km2)	Data Record Available	Stream Name
02093800	Rural	13.61	53.38	10-1-1955--Present	Reedy Fork
02094659	Urban	85.18	19.09	6-1-1999—Present	South Buffalo Creek
02095181	Urban	81.73	24.66	6-1-1999--Present	North Buffalo Creek

Durham County

Durham County is located in the north central portion of the Piedmont in North Carolina, very close to the fall line (Figure 5).

Figure 5. Durham County: Two stream stations are located along the Northeast Creek (0209741955 – Urban) in the Cape Fear watershed and on station along Mountain Creek (0208524090 – Rural), in the Neuse watershed.



The urban station for Durham County is Northeast Creek (0209741955 – Table 6) at SR1100 near Genlee and is located in the Cape Fear watershed. Northeast Creek has a drainage area of 54.57 km^2 with 39.08 % of impervious surface. The data quality for this station had one gap that lasted for a year and half.

The rural station is located in the Neuse watershed, Mountain Creek (0208524090) at SR1617 near Bahama and has a drainage area of 20.80 km^2; 5.48 % is covered by impervious surface. The data quality for this station has a gap of one day. In order to work around this and not have any gaps, the end date of the wateryears was moved up to fall before the gap. This still allowed sixteen years of data for processing, well over the minimum of ten years set as a requirement.

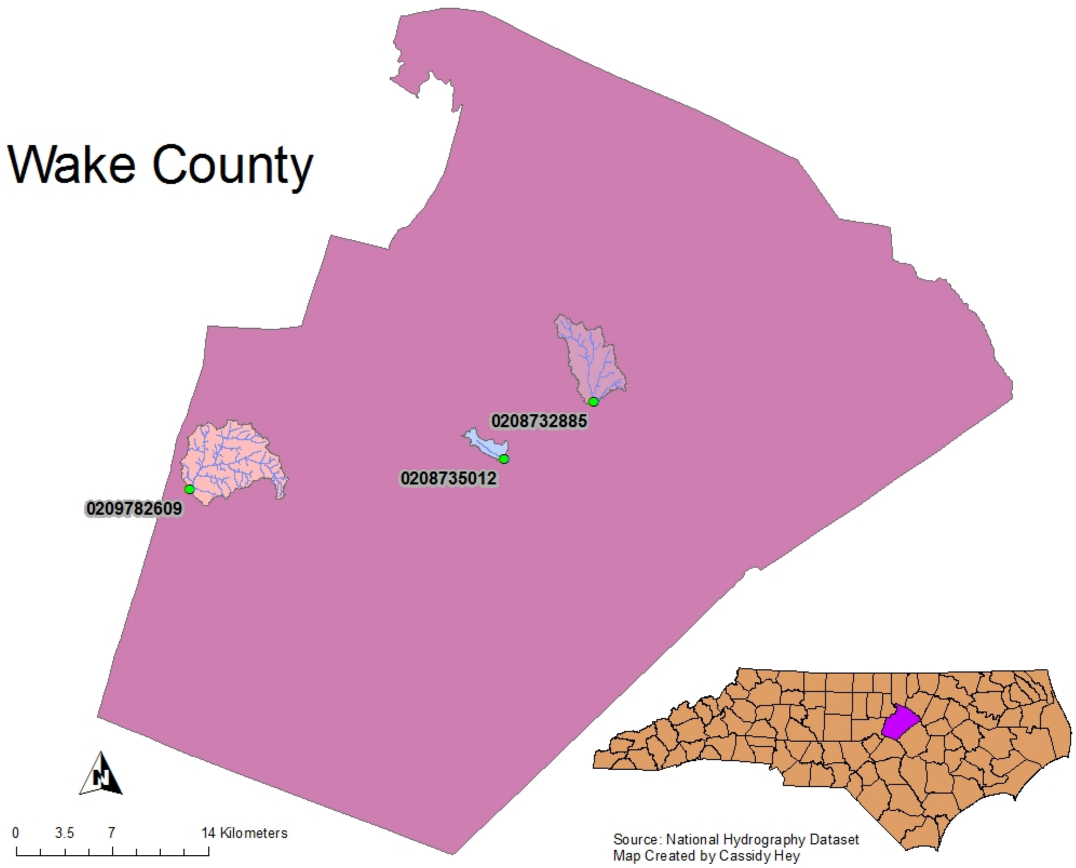
Table 6. Durham County urban and rural stream stations.

Site Number	Urban or Rural	% Impervious Area	Drainage Area (km2)	Data Record Available	Stream Name
0209741955	Urban	39.08	54.57	10-1-1982—Present	Northeast Creek
0208524090	Rural	5.48	20.8	10-1-1994—Present	Mountain Creek

Wake County

Wake County is located in the north central portion of North Carolina, in the Piedmont (Figure 6). Wake County has three watersheds that vary in size, two urban and one rural.

Figure 6. Wake County: Three stream stations are located along Rocky Branch Creek (0208735012 - Urban) and March Creek (0208732885 - Urban), both in the Neuse watershed; White Oak Creek stream station is (0209782609 - Rural) located in the Cape Fear watershed.



Rocky Branch Creek (0208735012) below Pullen Drive in Raleigh, March Creek (0208732885) near New Hope, and White Oak Creek (0209782609) at Mouth near Green level were the urban stations selected (Table 7). Rocky Branch Creek has a 3.06 km^2 drainage area, with nearly 87.94 % of the creek covered with impervious surface. Rocky Branch Creek has nearly fifteen years of consecutive data, starting in 1996. The USGS station actually started gathering data in 1992, for Rocky Branch Creek, but there were numerous time gaps, lasting a day to a few months. A decision was made to set the starting date at October 1, 1996, in order to optimize data quality. March Creek drainage area is 17.66 km^2 in size and has 69.24 % impervious surfaces. March Creek station accrued data for twenty-seven consecutive years with no gaps, starting in 1984. Rocky Branch Creek and March Creek stations are both located in the Neuse watershed.

White Oak Creek is the only rural station for this area, with a 31.12 km^2 drainage area and 25.16 % impervious surface. This station is located, in a different watershed than the urban stations, the Cape Fear watershed. The only gap for White Oak Creek was when the station started to gather data, and the start date was adjusted accordingly.

Table 7. Wake County urban and rural streams stations.

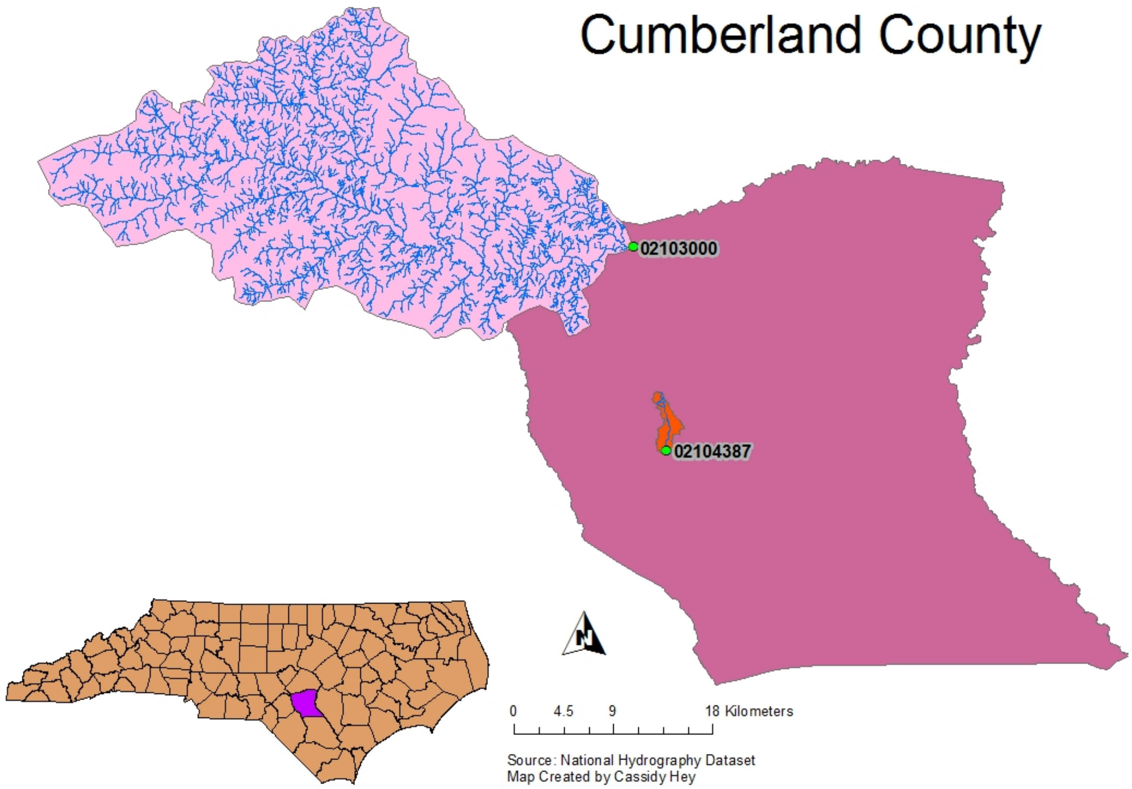
Site Number	Urban or Rural	% Impervious Area	Drainage Area (km2)	Calendar years	Stream Name
0208735012	Urban	87.94	3.06	6-26-1992—Present	Rocky Branch Creek
0208732885	Urban	69.24	17.66	1-1-1984—Present	Rocky Branch Creek
0209782609	Rural	25.16	31.12	9-1-1999—Present	White Oak Creek

Coastal Plain

Cumberland County

Cumberland County is located in the southeastern section of the Coastal Plain. The two stations chosen, one urban and one rural, both located in the Cape Fear watershed (Figure 7).

Figure 7 Cumberland County: Two stream stations are located along Buckhead Creek (02104387 - Urban), Little River (02103000 – Rural), both in the Cape Fear watershed.



Buckhead Creek (02104387) near Owens is the only urban station in the Coastal Plain, with a watershed size of 7.27 km^2 and 78.49 % impervious surface (Table 8). Buckhead Creek has sixteen years of data, but none of the data was consecutive. There were several gaps starting from 1976 and ending when the station stopped gathering data. In this case, there was no way to avoid the gaps. Some of the SAS software programs were not able to process the data while other programs will be able to account for the gaps.

The rural stations for Cumberland County contained the largest watersheds in this study. The use of software to delineate the streams and watersheds for these two stations proved to be very difficult and prone to error. This may be due to the lack of significant topographic relief in the Coastal Plain. After several attempts, the watershed boundaries ultimately had to be drawn in by hand. Little River (02103000) at Manchester has a watershed size of 892.61 km^2 and an impervious surface of 7.50 %. The stream station started gathering data in 1938. The station had a very large data gap that spanned several years, starting in 1950 and lasting until 2002. Due to the size and the location of the watershed portion or most of it may be located in the Piedmont. This may play a role in the outcome of the results.

Table 8. Cumberland County urban and rural stream stations.

Site Number	Urban or Rural	% Impervious Area	Drainage Area (km2)	Calendar Years	Stream Name
02104387	Urban	78.49	7.17	11-1-1976—8-14-1992	Buckhead Creek
02103000	Rural	7.50	892.61	10-1-1976—Present	Little River

Data

Topographic Data

North Carolina created the North Carolina Floodplain Mapping Program (NCFMP) in cooperation with Federal Emergency Management Agency (FEMA), in response to 14 federally declared disasters between 1989 and 1999. The idea was to better understand flood hazards and produce up-to-date digital Flood Insurance Rate Maps (FIRM). In order to accomplish this, Light Detection and Ranging (LiDAR) was used to produce digital elevation data from which valuable information was generated. Bare-earth mass points, bare-earth break lines, and 50 feet (ft) and 20 ft digital elevation models (DEM) were all generated from LiDAR and used to help update flood hazards data. This study utilized the 20 ft DEM to generate streams and watersheds for each study area. North Carolina had to be broken into sections, according to when the data was scheduled to be collected (Table 9).

Table 9. DEM published and delineated years

County	Published Year	Gathered
Buncombe	Aug-06	March - April 2005
Cumberland	2004	Spring 2001
Wake	May-02	Jan - March 2001
Durham	2004	Spring 2001
Mecklenburg	Sep-04	Jan - February 2003
Guilford	2004	Spring 2001

Land use-land cover data

The 2006 Nation Land Cover Database (NCLD) was created to help identify significant changes in land cover, urban development, and help meet end users needs for a timely update in land cover changes (Xian et al., 2009). Prior to 2006 data release, which was made public in the spring of 2011, data was from the year 2001. The idea behind NLCD 2006 was to have a 5-year turn around instead of a 10-year cycle and to help detect changes and patterns that occurred between 2001 and 2006 (Xian et al., 2009).

The NLCD released the 2006 land cover, land cover change, and percent developed imperviousness, and an updated version of NLCD 2001. The 2006 data reflected 30 m land cover classification changes for the contiguous US, generated mostly from unsupervised classification from Landsat Enhanced Thematic Mapper+ (ETM+) via 2006 (Fry et al., 2011). An additional part of the 2006 product release was an updated version of 2001, percent-developed imperviousness change (Fry et al., 2011). This product contained the change in imperviousness values that were different between 2001 and 2006 (Fry et al., 2011). For the purpose of this study, the 2006 NLCD impervious surface will be used to help verify urban areas and to calculate impervious surface areas within each study site watershed.

Streamflow data

The USGS offers free real-time streamflow data on their web site for the entire nation. The real-time data is usually collected in intervals of 15 to 60 minutes and is stored on site (USGS, 2011). Roughly every 1 to 4 hours, the data is transmitted to the USGS offices wirelessly (USGS, 2011). The purpose for real-time streamflow data is to track short-term changes over several hours in rivers and streams. For this study, most of the data appeared to be measured; at times the data was estimated or not recorded for a day to a few years. A gap in the data existed on several study sites of this research. For each site the data available varied, but most offered real time, daily, monthly, annual, and peak streamflow statistics all measured in cubic feet per second (cfs). The length of data differed at each site for several reasons, funding being the biggest. The data was available in either graph or table format. For this study, the daily mean discharge in a tab format was used to track changes over the years by applying different streamflow metrics to each site.

Methods

Stream and Watershed Delineation

Watersheds were generated in ArcGIS for each stream station chosen. The watershed area that the USGS has listed on their website for each station may vary from the watershed calculated for this research. This was due to one of the following reasons: the data used, different data equals different results, or use of a different delineation method. The difference between the USGS watershed areas and the watersheds generated for this study were minimal.

There were several steps involved to generate streams and watersheds. The first step was to generate or obtain a DEM. For this study, the DEMs were downloaded from the North Carolina Floodplain Mapping Program to help save time instead of generating them from LiDAR data. The DEM's were downloaded in sections for the targeted counties. Due to their large file size each section had to be pieced together in order to create a DEM that covered the entire county in ArcGIS.

The process of stream and watershed delineation following completion of the DEM is summarized in Table 10. This table also describes where to find the tool needed in ArcGIS to create and delineate streams.

Table 10. Generating streams and watersheds from DEMs in ArcGIS.

Toolbox: Spatial Analyst - Hydrology	
Fill	Removes small imperfections in the DEM.
Flow Direction	Determines into which nearby neighboring pixel any water might flow naturally.
Flow Accumulation	Generated from counting the cumulative number of pixels that naturally flow or drain into outlets. This step is used to find the drainage pattern of a terrain.
Toolbox: Spatial Analyst - Conditional	
Con	This is a true or false statement that requires a command line which evaluates each cell of the input cells of input raters.
Toolbox: Spatial Analyst - Hydrology	
Stream Link	Is meant to be used for sections of stream channel connecting two successive junctions, a junction and the outlet, or a junction and the drainage divide.
Snap Pour Point	Is used to make sure that the high accumulated flow points are selected when delineating drainage area.
Watershed	The area that flows into an outlet or pour point.
Spatial Analyst toolbar:	
Convert - Raster to Features	A rater is to be converted to a shapefile.

The fill tool fills sinks found along the surface of the DEM and should be the first step when doing any hydrologic modeling. Sinks are areas that do not drain anywhere and can create an endless processing loop where cells attempt to drain into each other. The reason for filling sinks was for the drainage network to be built which located the flow path of every cell.

Flow direction was the next step, which is important, because it determined where the landscape drained and the direction of flow for each cell. For every cell being processed, the program located the steepest downward descent to create a grid. Next was flow accumulation, this helped delineate streams and watersheds and provided the ultimate path flow of every cell within the DEM. The purpose of flow accumulation is to generate a drainage network that was based on the direction of the flow of each cell.

The con step helped adjust the numbers of the streams generated based on the amount of streams the program generated. After stream segments were generated, from the con, the stream link tool was used to connect streams together.

The next step was the snap pour point tool. The snap pour point was used to snap the stream gage shapfile to the nearest high flow accumulation.

Impervious surface area

The NLCD 2006 impervious surface was clipped for each study's watershed; once the surface was clipped, the raster was converted to a shapefile. Converting the raster to a feature allowed for more flexibility working with the impervious surface in ArcGIS. Once the impervious surface was converted and the total impervious surface was extracted, the total area of impervious surface was divided by the total area of the watershed to determine the percent impervious surface within that watershed (Table 11).

Table 11. Percent impervious surface for each area

Site Number	County	Region	Urban or Rural	Impervious Area 2006 km2	Drainage Area (km2)	Percent Impervious Area
0344894205	Buncombe	Mountains	Rural	0.31	37.5	0.84
03450000	Buncombe	Mountains	Rural	0.07	14.17	0.49
03451000	Buncombe	Mountains	Urban	44.80	336.52	13.31
02104387	Cumberland	Coastal	Urban	5.63	7.17	78.49
02103000	Cumberland	Coastal	Rural	66.94	892.61	7.50
0214657975	Mecklenburg	Piedmont	Rural	7.93	21.7	36.56
02146409	Mecklenburg	Piedmont	Urban	28.0	30.35	92.26
0214627970	Mecklenburg	Piedmont	Urban	18.11	23.51	77.03
02093800	Guilford	Piedmont	Rural	7.26	53.38	13.61
02094659	Guilford	Piedmont	Urban	16.26	19.09	85.18
02095181	Guilford	Piedmont	Urban	20.15	24.66	81.73
0208735012	Wake	Piedmont	Urban	2.69	3.06	87.94
0208732885	Wake	Piedmont	Urban	12.23	17.66	69.24
0208782609	Wake	Piedmont	Rural	7.83	31.12	25.16
0209741955	Durham	Piedmont	Urban	21.33	54.57	39.08
0208524090	Durham	Piedmont	Rural	1.14	20.8	5.48

Metrics of Streamflow

When choosing the different metrics, it was intended to have streamflow metrics with little to no overlap. Originally, a total of forty metrics were chosen, but this list was narrowed due to one or more of the following reasons:

redundancy, had no bearing on this study, inadequate data, or insufficient information to fully understand the metric. Examples of the redundant metric include Annual Mean Discharge (Q_{mean}) and Mean Annual Run-off (Q_{mean}/area) (Hughes and Omernik (1983), both of which were closely tied to Mean Annual Daily Flow, and therefore, were not used. A total of nine streamflow metrics (Table 12) were used to examine the streamflow data for this study.

Table 12: Streamflow Metrics Used in the Study

Streamflow metrics	Definition
Mean Annual Daily Flow	Mean Annual Daily Flow divided by the area of each watershed
Minimum Annual Daily Flow	Minimum Annual Daily Flow divided by the area of each watershed
Maximum Annual Daily Flow	Maximum Annual Daily Flow divided by the area of each watershed
T_{Qmean}	Fraction of a year the daily mean discharge exceeds the annual mean discharge (Booth, 2004)
Coefficient of Variation (DAYCV)	DAYCV is the average, across all years, of the standard deviation of the daily flows divided by the annual mean daily flow, (Poff, 1996)
Baseflow Index (BFI)	BFI is the average annual ratio of the lowest daily flow to the mean daily (Poff, 1996)
Highflow Index	Ratio of the highest daily mean flow to the annual mean daily flow
Range Index	The difference between the highest and lowest daily mean flow scaled by the annual mean daily flow
Flow Duration Curve	Q_{10}-Q_{95}/Q_{50}

The mean, minimum, and maximum annual daily flows were divided by the area of each watershed, because of the different size watersheds for each site. This allowed for a more accurate comparison of each county when examining the mean, minimum, and maximum annual daily flow.

The metric T_{Qmean} is a measure of daily streamflow through time and is compared to the mean discharge of a streamflow (Booth, 2004). Periods where streamflow is high and then rapidly recedes, the T_{Qmean} is low, i.e. an urban area (Konrad and Booth, 2002). Ideally T_{Qmean} will have a higher value in a rural area as apposed to an urban environment. DAYCV is the ratio of the standard deviation to the mean. DAYCV is useful in looking at data where the changes of the variability increase drastically along with an increase in the mean.

BFI metric reflects low stability and can be compared on a year to year basis to understand the overall baseflow for the streams. The calculations of BFI are found by averaging the annual ratio of the lowest daily flow to the mean daily. If possible, the results would show rural streams having a higher value than the urban streams. Range index, on the other hand, is the difference between the highest and lowest daily mean flow scaled divided by the annual mean daily flow. Urban streams are expected to have a higher value than their counterpart the rural stream. Highflow index is calculated by the lowest daily mean flow to the annual mean daily flow. Ideally, the highflow index would have a high value for an urban setting and a low value in a rural area.

Q_{10}-Q_{95}/Q_{50} is useful at determining the variability or flashiness of streamflow, as well as, how the discharge of a stream is sustained over time. The factors to determine the flow duration curve are determined by several variables including climate, watershed land cover/land use, soil type, and topography. In a perfect world, an urban area will have a higher value compared to a rural watershed. Q10 indices correspond to high flows that are equaled or exceeded only 10 percent of the time. Whereas Q95 indices are low flows that are equaled or exceeded 95 percent of the time. Q50 is considered as the medium flow, equaled or exceeded 50 percent of the time, respectively.

Data Analysis

All the streamflow metrics are calculated from flow data using SAS, a software package for statistical analysis (SAS, 2011). The SAS programs for this study were written by Dr. Zhi-Jun Liu. For coefficient of variation (DAYCV) and (Q10-Q95)/Q50, the metrics values are calculated for the entire study period. For the other seven metrics, their annual values are calculated. As such, only complete years with 365 or 366 days are used in analysis. For metrics on an annual basis, time series plots are made using Excel. The plots are then evaluated and compared between rural and urban stations.

CHAPTER IV

RESULTS

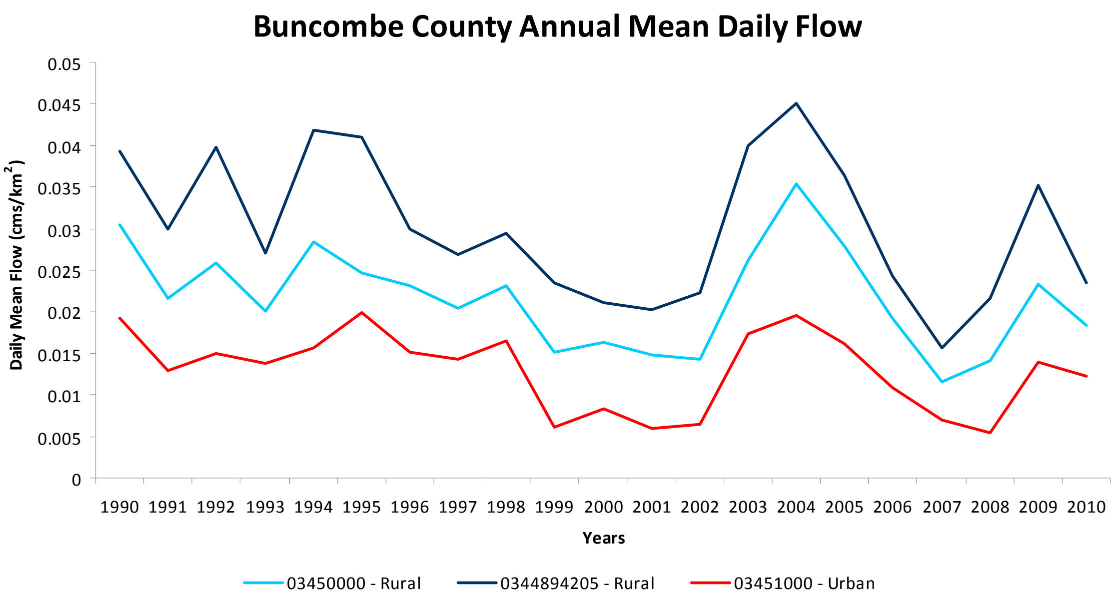
Mountains

Buncombe County

Flow data from three stations in this county were analyzed and evaluated.

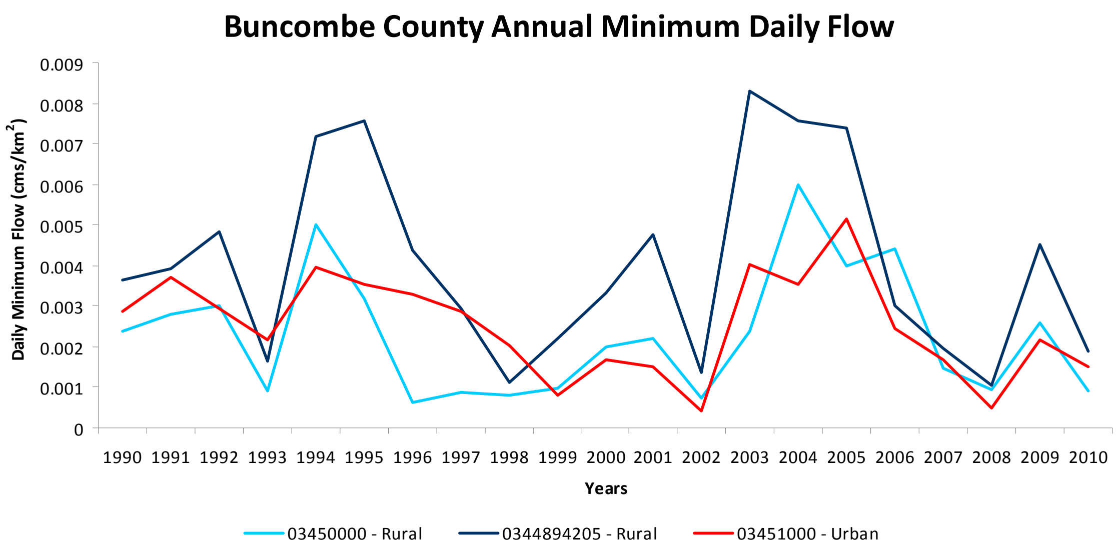
Annual Mean Daily Flow As shown in Figure 8 the rural stream (North Fork Swannanoa, 0344894205) with the most impervious surface in its watershed has the highest annual mean daily flow; the urban stream has the lowest (Swannanoa River, 03451000). There was a noticeable high peak for year 2004, due to two major hurricanes that caused significant flooding and major damage to the mountain region.

Figure 8. Annual Mean Daily Flow results for Buncombe County stations.



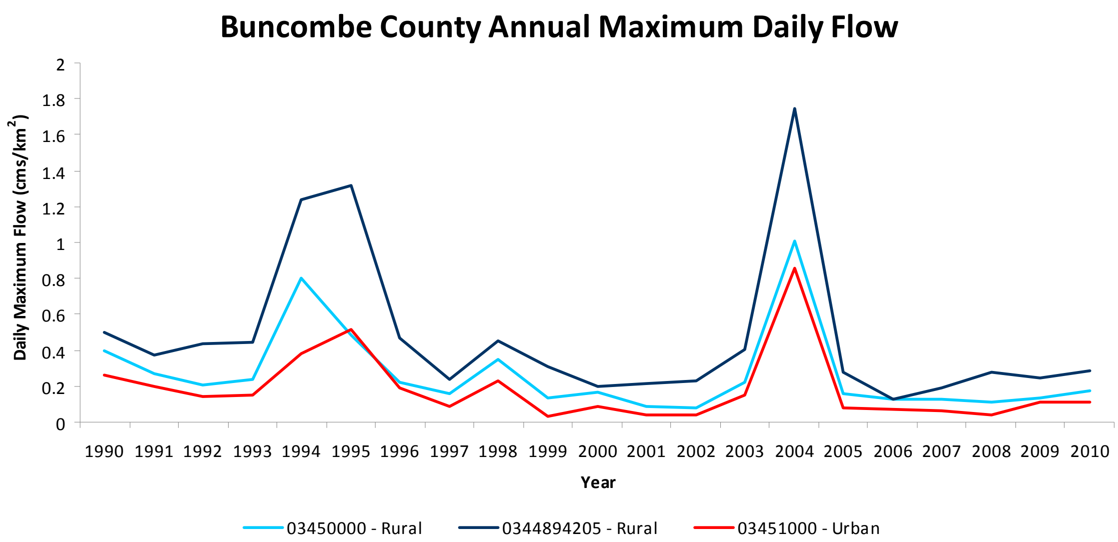
Annual Minimum Daily Flow Figure 9 shows that in most years of the study period, the rural stream (North Fork Swannanoa, 0344894205), with the highest amount of impervious surface overall, had the highest minimum daily flows. The urban stream (Swannanoa River, 03451000) had relatively lower minimum daily flow in most years.

Figure 9. Annual Minimum Daily Flow results for Buncombe County stations.



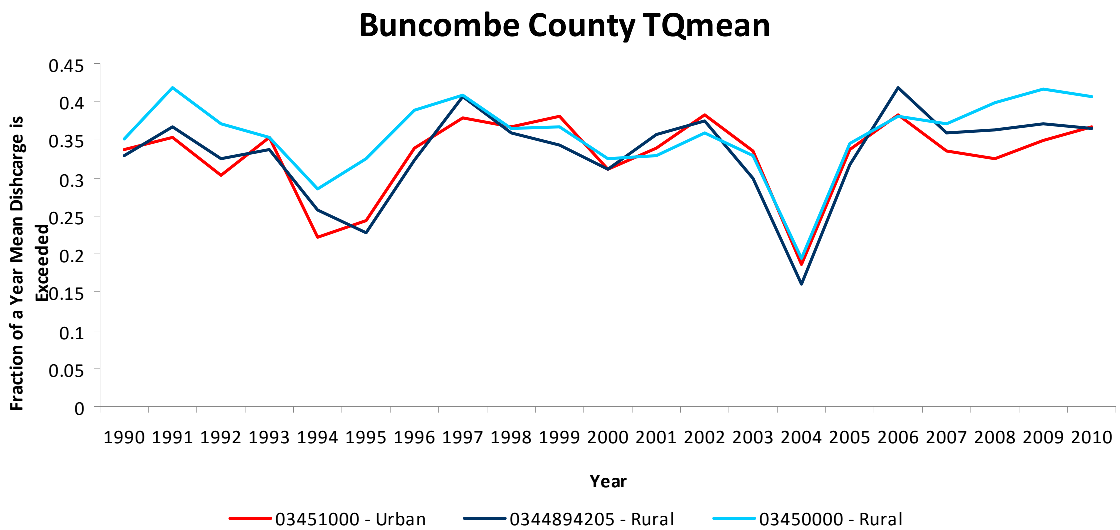
Annual Maximum Daily Flow The time series plots for this metric are shown in Figure 10. There are two marked peaks in the plots. The first occurred between 1994 and 1995, this is possibly from hurricanes. The other high peak occurred in 2004, this was the result of two major hurricanes occurring back-to-back, Frances and Ivan, which swept through the mountain region causing major damages and flooding. In most years, the urban station (Swannanoa River, 03451000) had the lower annual maximum daily flows than the two rural streams (North Fork Swannanoa, 0344894205 and Beetree Creek, 03450000).

Figure 10. Annual Maximum Daily Flow results for Buncombe County stations.



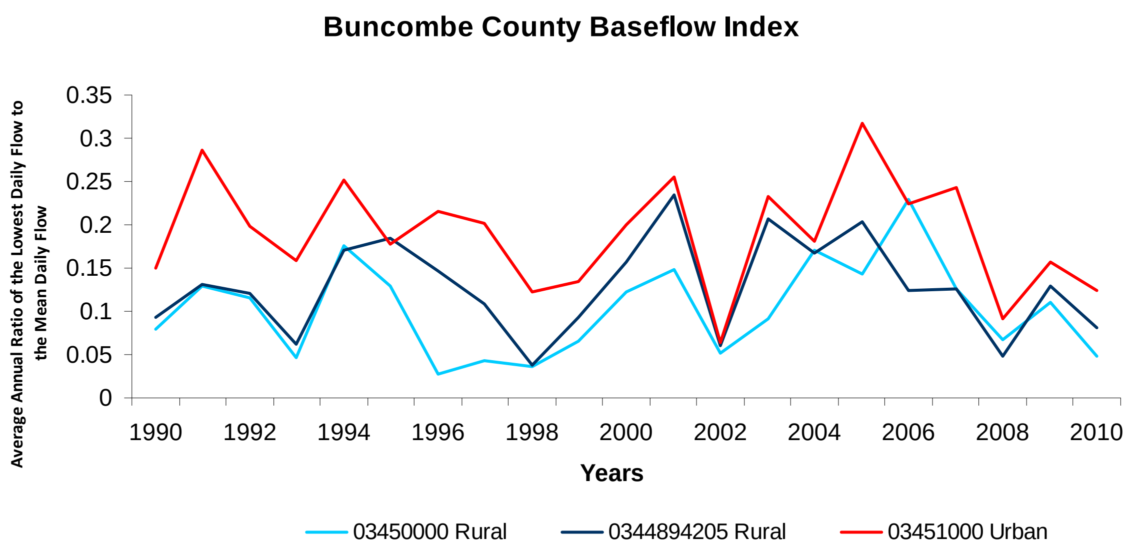
T_{Qmean} The time series plots for this metric are shown in Figure 11. Although in early years of the study period, the urban station had lower values than its rural counterparts, there is no clear pattern later that separates the urban station from the rural stations.

Figure 11. T_{Qmean} results for Buncombe County stations.



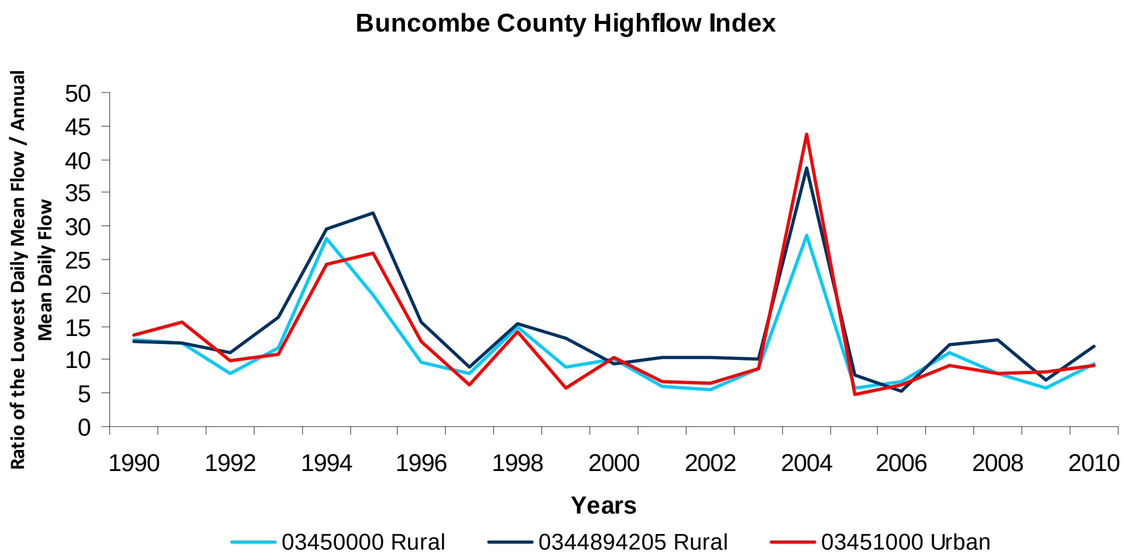
Baseflow Index Figure 12 shows that in most years, the urban stream had higher values of baseflow index than its two rural counterparts.

Figure 12. Baseflow Index results for Buncombe County stations.



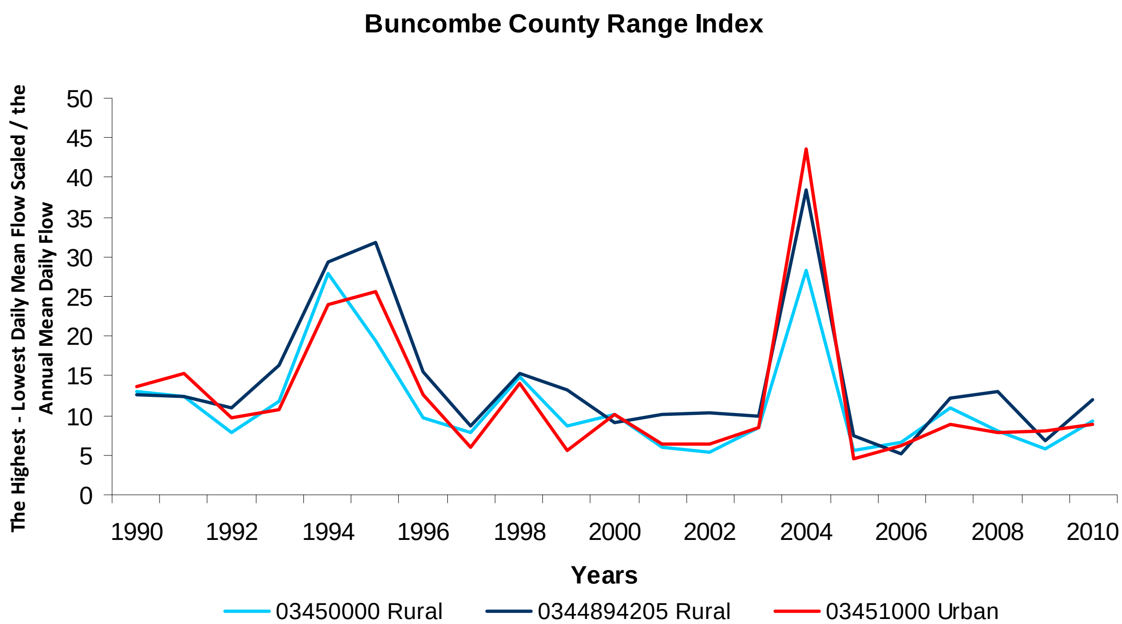
Highflow Index As shown in Figure 13, the urban stream had higher values of highflow index in some years, but lower values in most years than the two rural streams.

Figure 13. Highflow Index results for Buncombe County stations.



Range Index The pattern of this metric is similar to that of highflow index (Figure 14). That is, the urban stream had higher values in some years, but lower values in most years than the two rural streams.

Figure 14. Range Index results for Buncombe County stations.



Flow Duration Curve and DAYCV The values for these two metrics are given in Table 13. The urban stream had a higher DAYCV value (141.7) than one rural stream (135.0), but lower than the other rural stream (166.9). The values of (Q10-Q95)/Q50 showed the same pattern. The urban station has a value of 2.69. The two rural stations have a value of 2.59 and 2.85, respectively.

Table 13. Flow Duration Curve and Coefficient of Variation Results for Buncombe County.

County	Site Number	Region	Urban or Rural	DAYCV	Q10-Q95/Q50
Buncombe	0344894205	Mountains	Rural	166.9	2.60
Buncombe	03450000	Mountains	Rural	135.0	2.85
Buncombe	03451000	Mountains	Urban	141.7	2.69

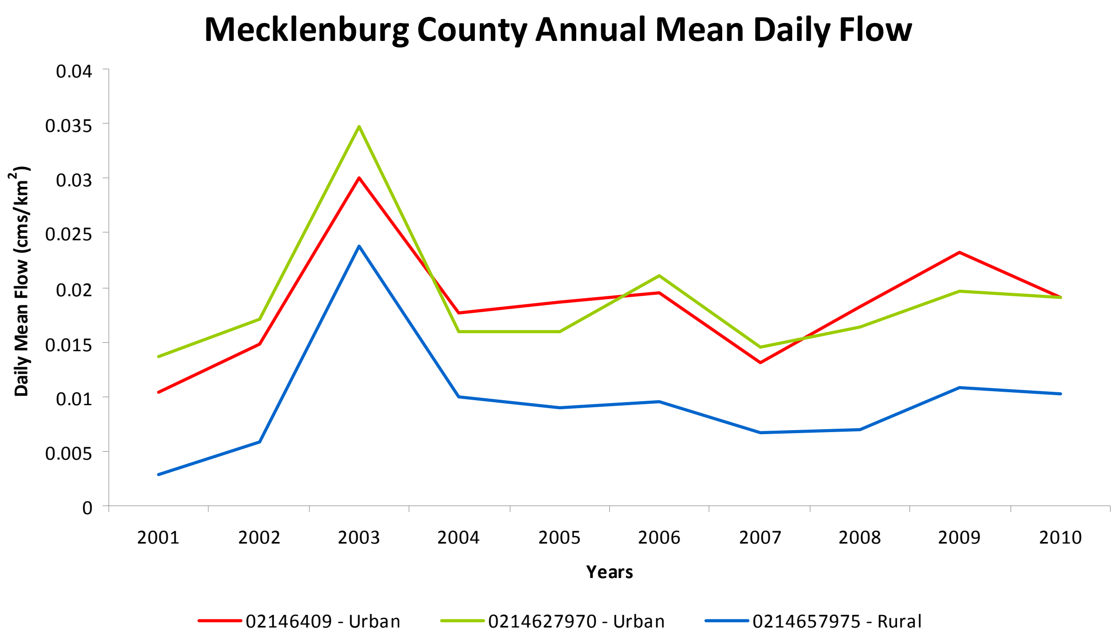
Piedmont

Mecklenburg County

Flow data from three stations in this county were analyzed and evaluated.

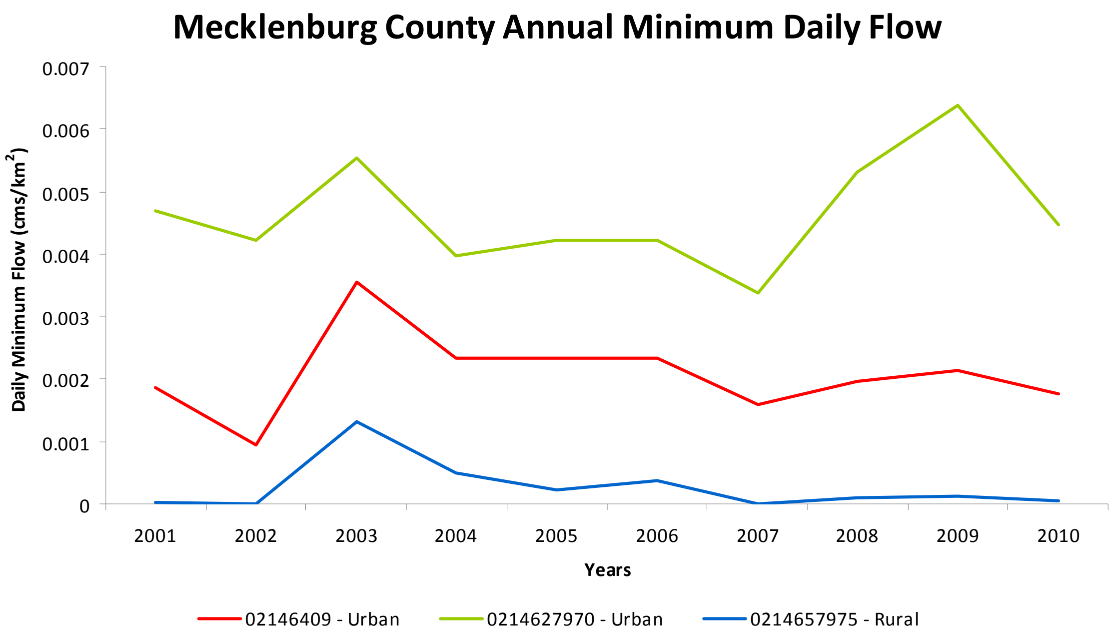
Annual Mean Daily Flow As shown in Figure 15 the urban streams (Little Sugar Creek, 02146409; Stewart Creek, 021427970) have the highest annual mean daily flow; the rural stream has the lowest (Irvins Creek, 0214657975).

Figure 15. Annual Mean Daily Flow results for Mecklenburg County stations.



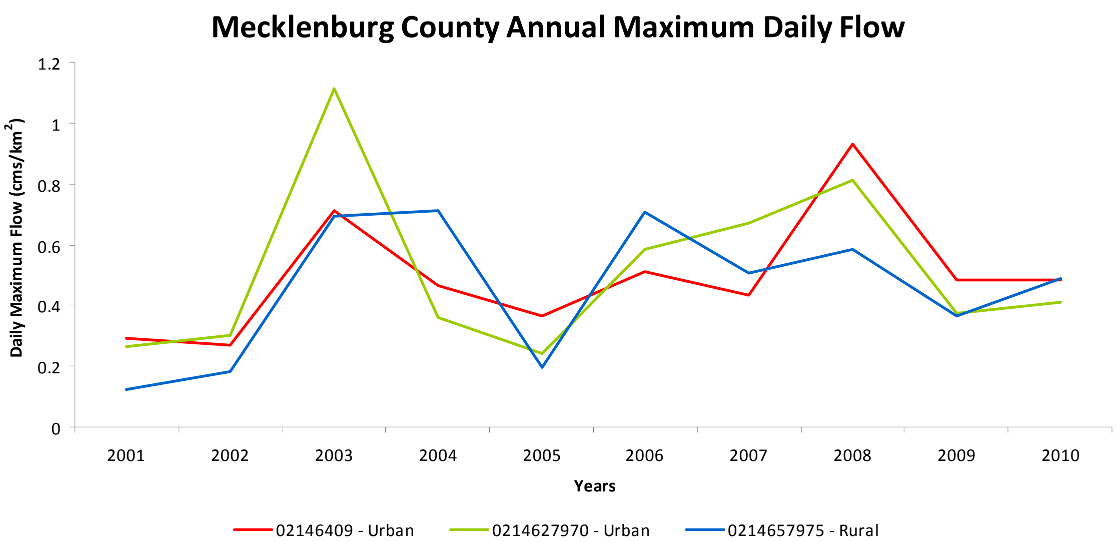
Annual Minimum Daily Flow Figure 16 shows that the urban streams (Little Sugar Creek, 02146409; Stewart Creek, 021427970) have the highest annual minimum daily flow; the rural stream has the lowest (Irvins Creek, 0214657975).

Figure 16. Annual Minimum Daily results for Mecklenburg County stations.



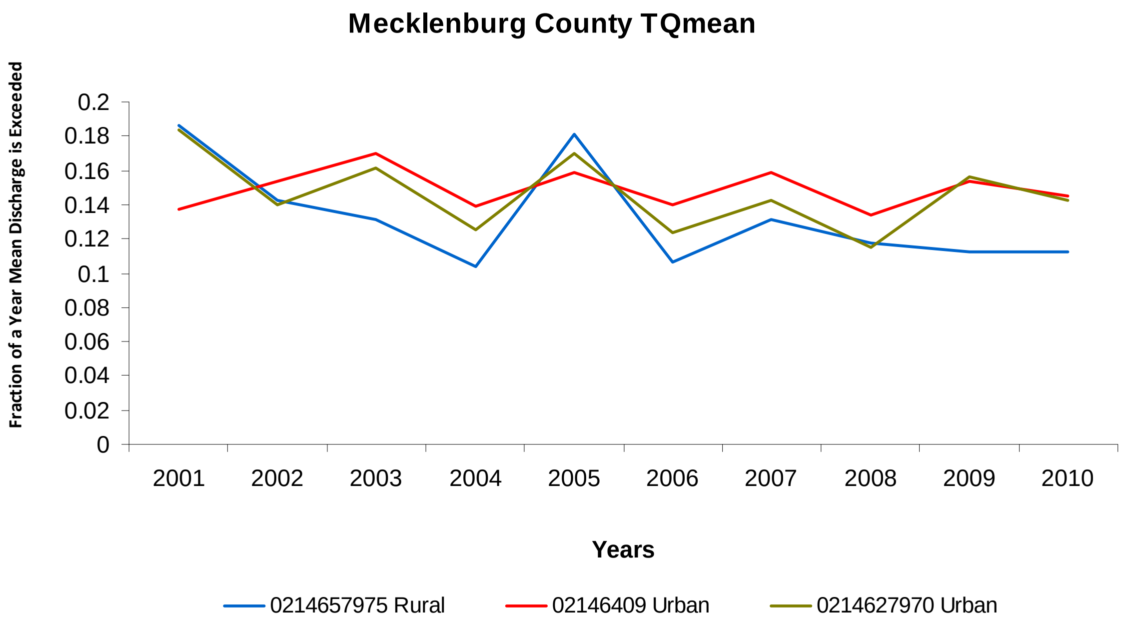
Annual Maximum Daily Flow In most years (Figure 17), the urban stations (Little Sugar Creek, 02146409; Stewart Creek, 021427970) had the highest annual maximum daily flows than the rural stream (Irvins Creek, 0214657975).

Figure 17. Annual Maximum Daily Flow results for Mecklenburg County stations.



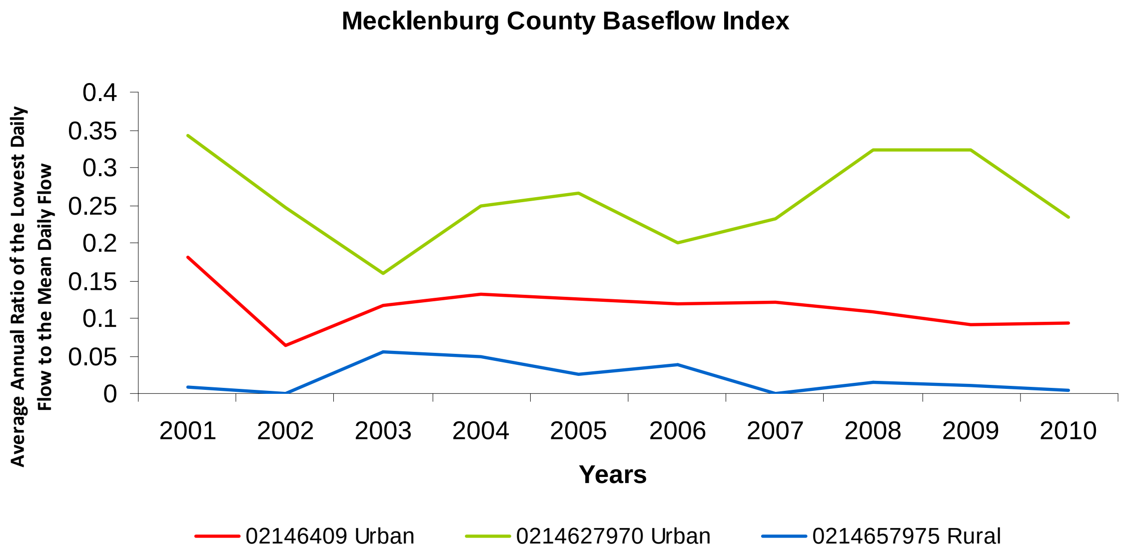
T_{Qmean} The time series plots for this metric are shown in Figure 18. The urban streams had higher values in some years, while the rural stream had lower values comparatively.

Figure 18. T_{Qmean} results for Mecklenburg County stations.



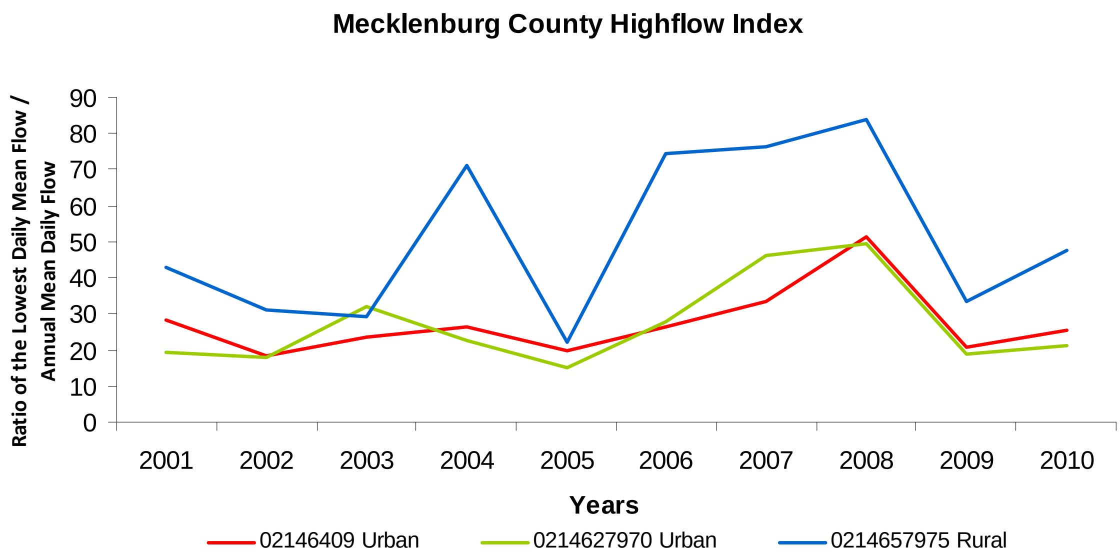
Baseflow Index The urban stations had the highest baseflow index than the rural stream (Figure 19).

Figure 19. Baseflow Index results for Mecklenburg County stations



Highflow Index As shown in Figure 20, the rural stream had higher values of the highflow index for most of the years; the two urban streams had the lower values.

Figure 20. Highflow Index results for Mecklenburg County stations.



Range Index The pattern of this metric is similar to that of highflow index (Figure 21). That is, the rural stream had higher values in most of the years, but the two urban streams had the lower values in most years.

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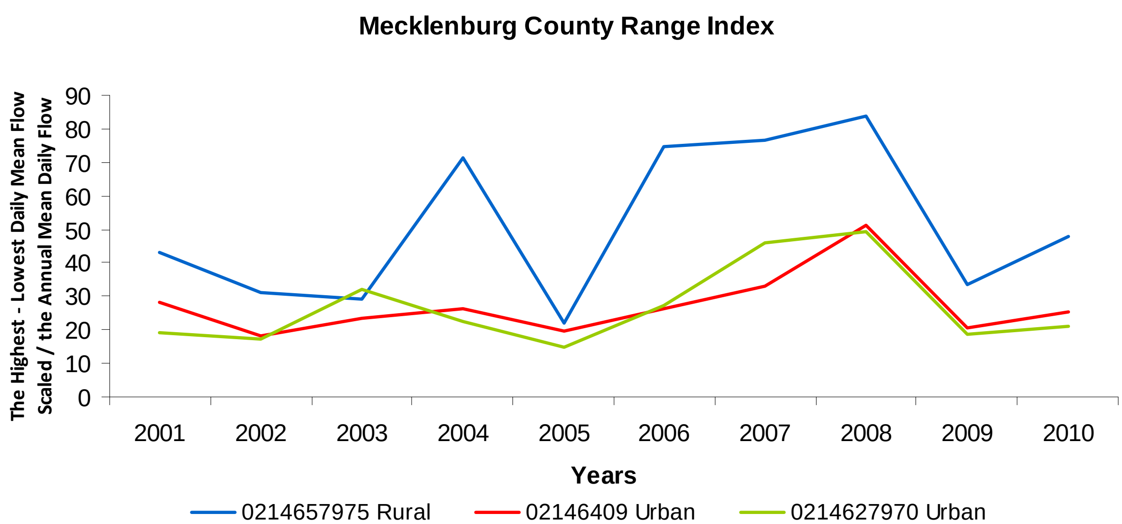
Figure 21. Range Index results for Mecklenburg County stations.



Flow Duration Curve and DAYCV The values for these two metrics are given in Table 14. The two urban streams had the lower DAYCV value than the one rural stream. The values of (Q10-Q95)/Q50 showed a different pattern. The urban stations have the highest (6.31) and lowest (2.42) values. The rural station has the medium value of 5.29.

Table 14. Flow Duration Curve and Coefficient of Variation Results for Mecklenburg County.

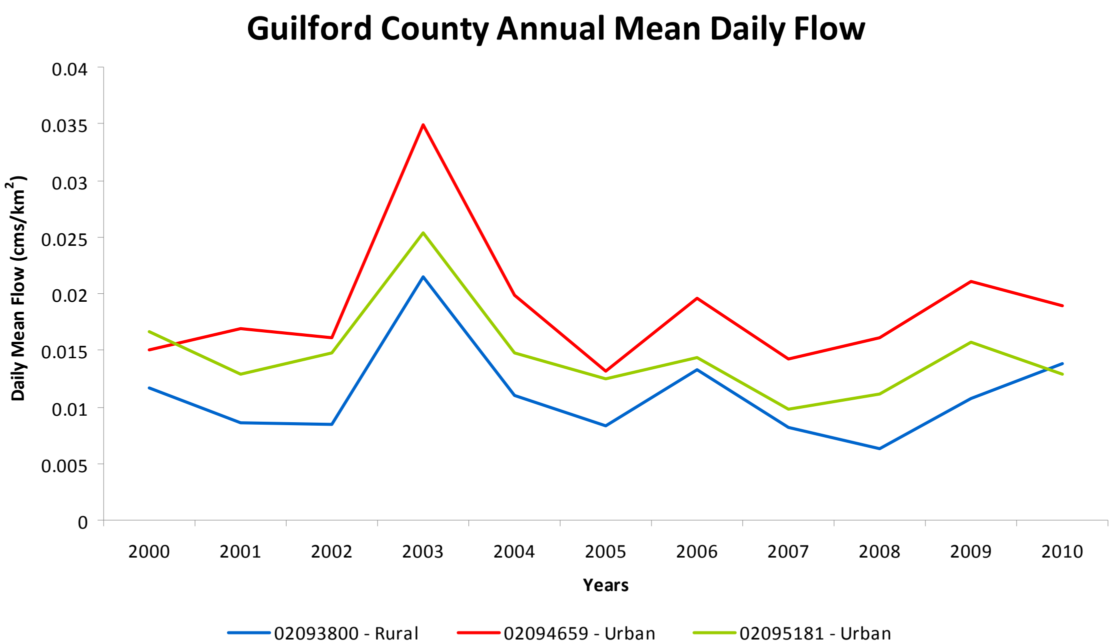
County	Site Number	Region	Urban or Rural	DAYCV	Q10-Q95/Q50
Mecklenburg	0214657975	Piedmont	Rural	426.5	5.29
Mecklenburg	02146409	Piedmont	Urban	301.8	6.31
Mecklenburg	0214627970	Piedmont	Urban	253.6	2.42

Guilford County

Flow data from three stations in this county were analyzed and evaluated.

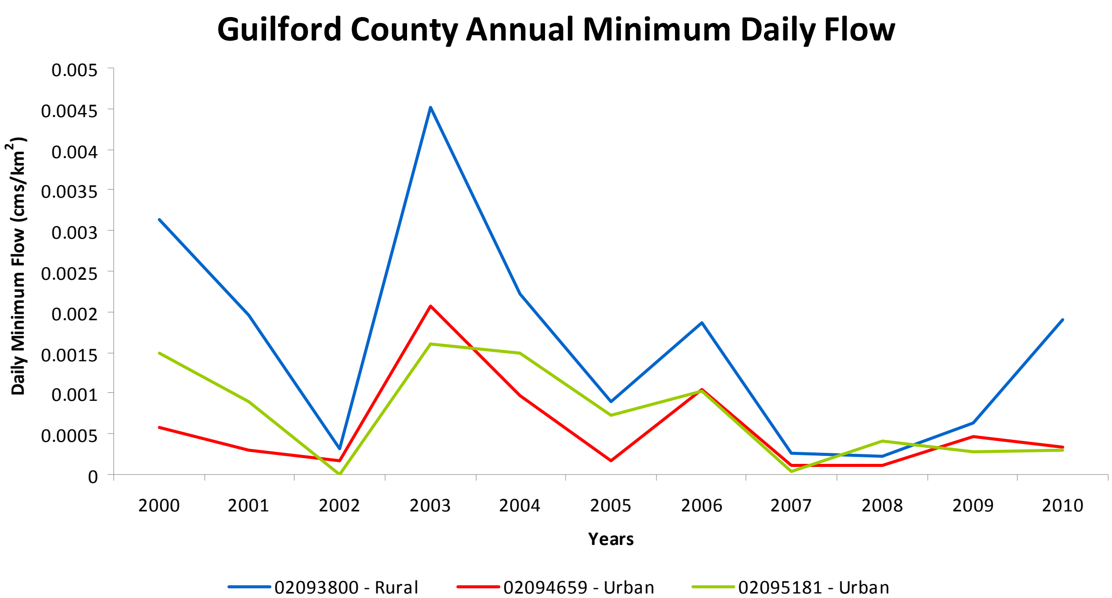
Annual Mean Daily Flow As shown in Figure 22 the urban streams (South Buffalo Creek, 02094659; North Buffalo Creek, 02095181) had the higher annual mean daily flow values; the rural stream had the lowest value (Reedy Fork, 02093800).

Figure 22. Annual Mean Daily Flow results for Guilford County stations.



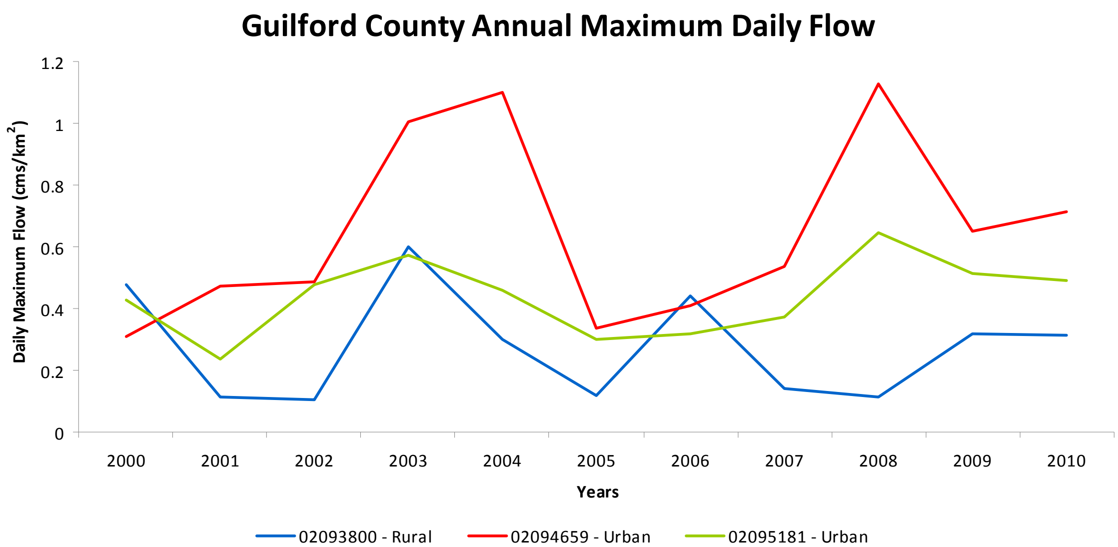
Annual Minimum Daily Flow Figure 23 shows that in most years, the rural stream (Reedy Fork, 02093800) had the highest minimum daily flows values. The urban streams (South Buffalo Creek, 02094659; North Buffalo Creek, 02095181) had relatively lower minimum daily flow in most years.

Figure 23. Annual Minimum Daily Flow results for Guilford County stations.



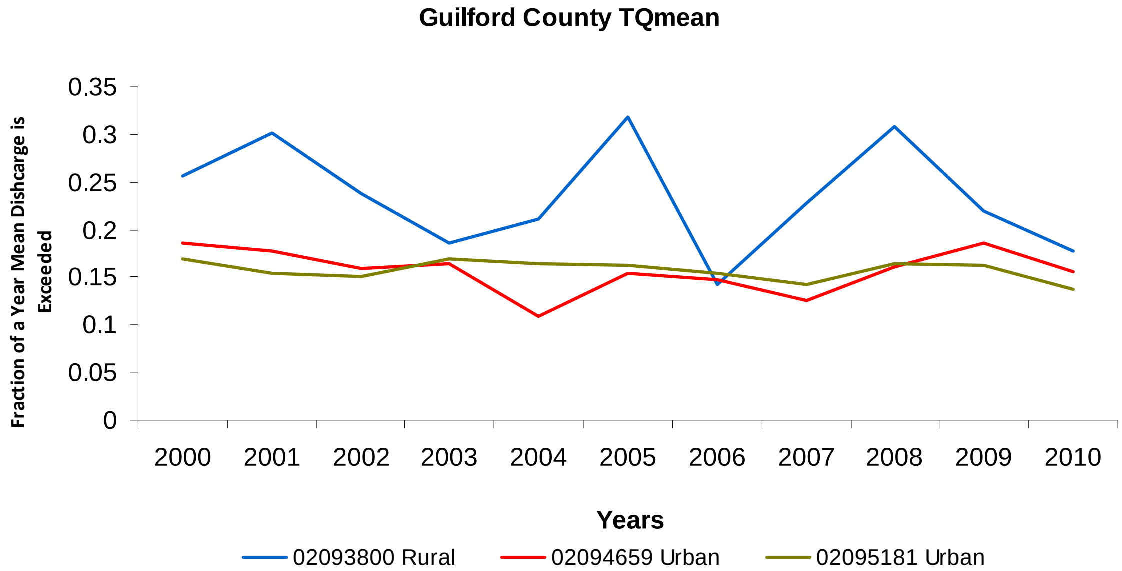
Annual Maximum Daily Flow The time series plots for this metric are shown in Figure 24. In most years, the urban station (South Buffalo Creek, 02094659), with the most impervious surface, had the higher annual maximum daily flows values than the rural stream (Reedy Fork, 02093800).

Figure 24. Annual Maximum Daily Flow results for Guilford County stations.



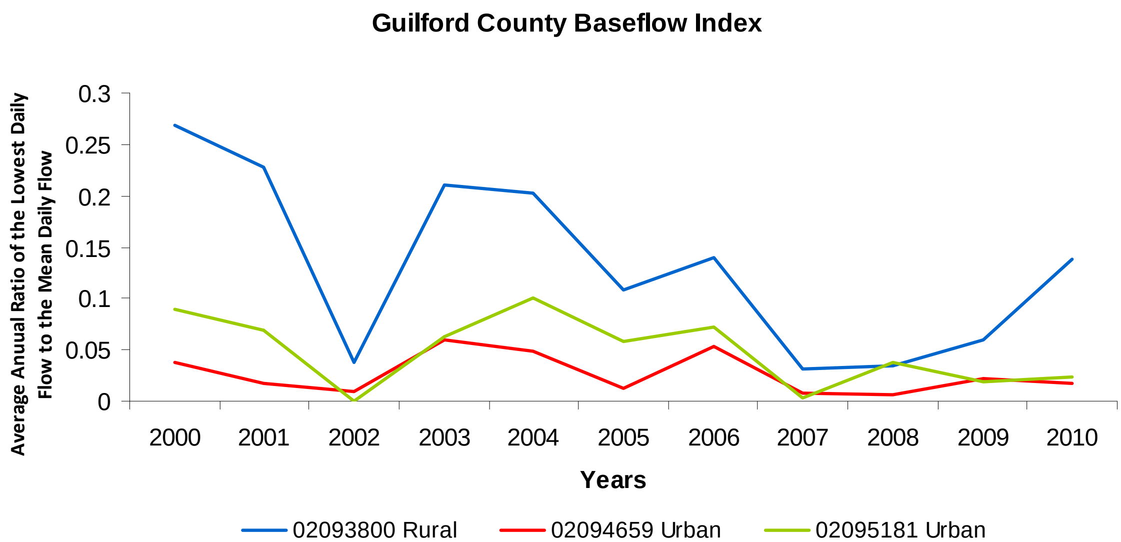
T_{Qmean} The time series plots for this metric are shown in Figure 25. The rural station had the higher values than its urban counterparts.

Figure 25. T_{Qmean} results for Guilford County stations.



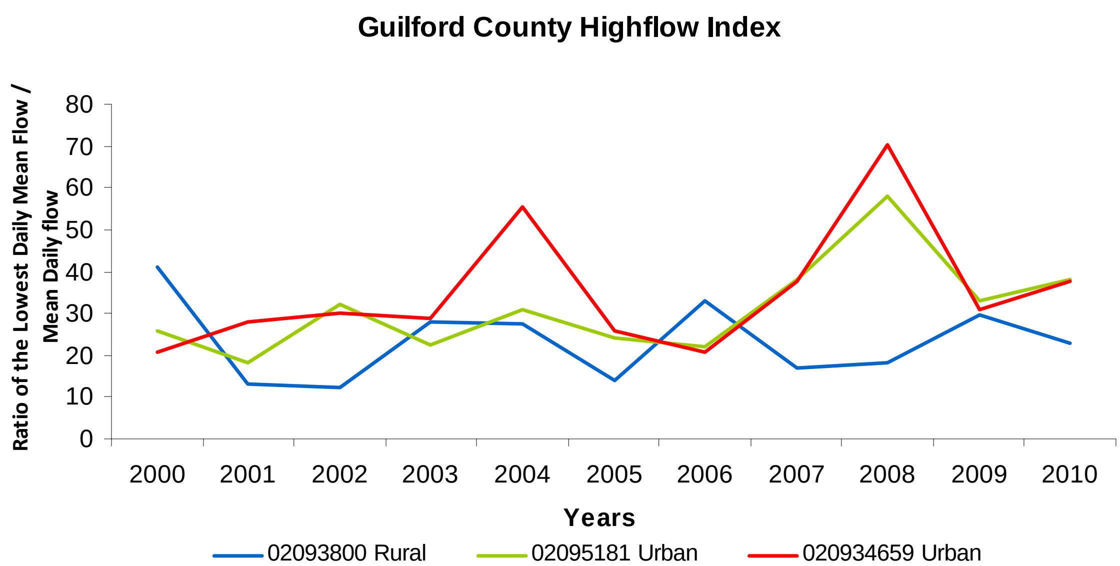
Baseflow Index Figure 26 shows that in most years, the rural stream had higher values of baseflow index than its two urban counterparts.

Figure 26. Baseflow Index results for Guilford County stations.



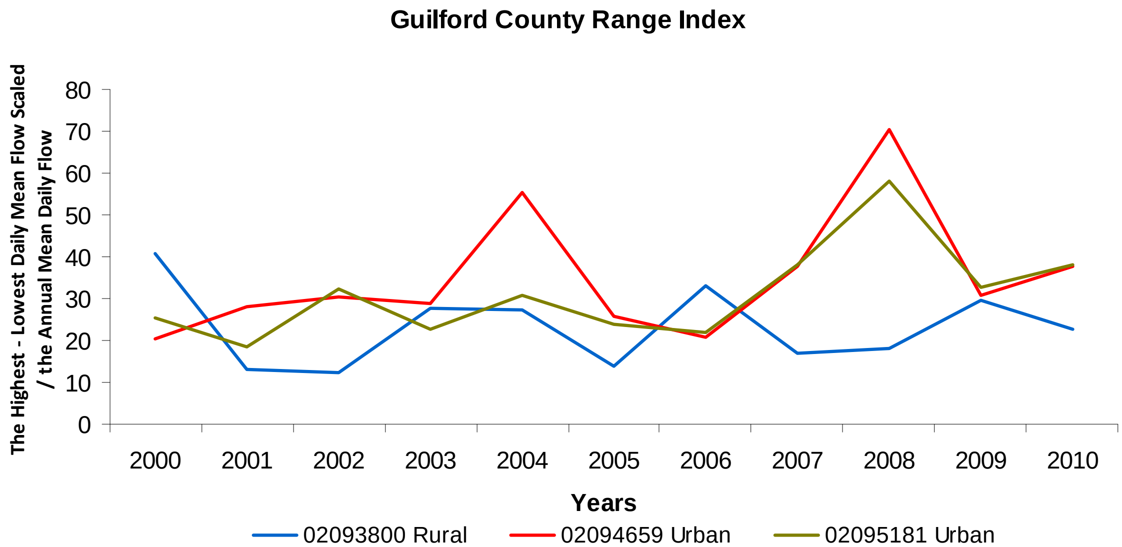
Highflow Index As shown in Figure 27, the urban stream had higher values of highflow index in some years than the rural stream.

Figure 27. Highflow Index results Guilford County stations.



Range Index The pattern of this metric is similar to that of highflow index (Figure 28). That is, the urban stream had higher values in most years than the rural stream.

Figure 28. Range Index results for Guilford County stations.



Flow Duration Curve and DAYCV The values for these two metrics are given in Table 15. The urban streams had higher DAYCV values (328.9 and 288.1) than the rural stream (199.4). The values of (Q10-Q95)/Q50 showed the same pattern. The urban stations have values (10.21 and 7.47). The rural station has a value of 2.36, respectively.

Table 15. Flow Duration Curve and Coefficient of Variation Results for Guilford County.

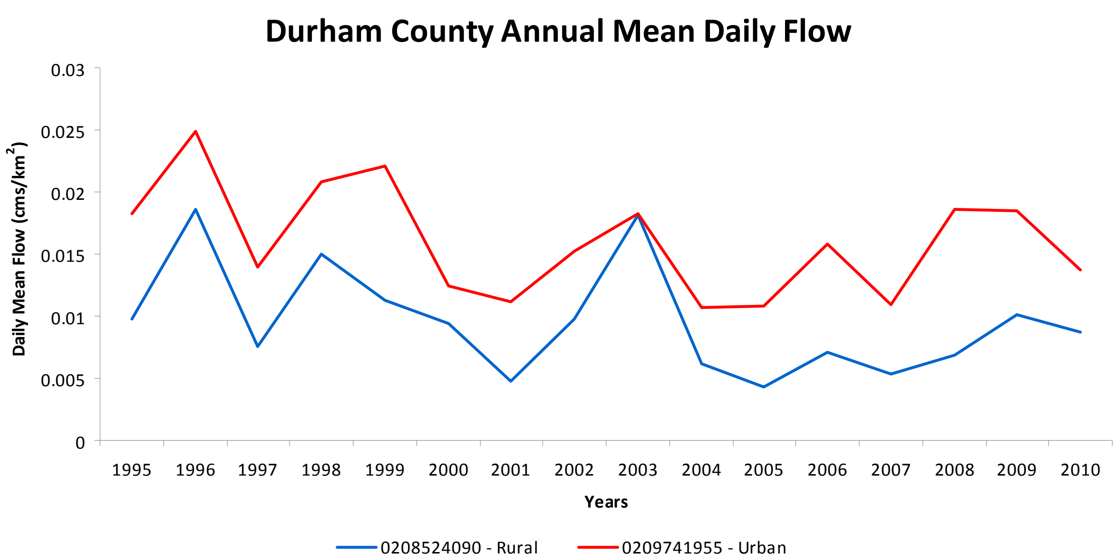
County	Site Number	Region	Urban or Rural	DAYCV	Q10-Q95/Q50
Guilford	02093800	Piedmont	Rural	199.4	2.36
Guilford	02094659	Piedmont	Urban	328.9	10.21
Guilford	02095181	Piedmont	Urban	288.1	7.47

Durham County

Flow data from two stations in this county were analyzed and evaluated.

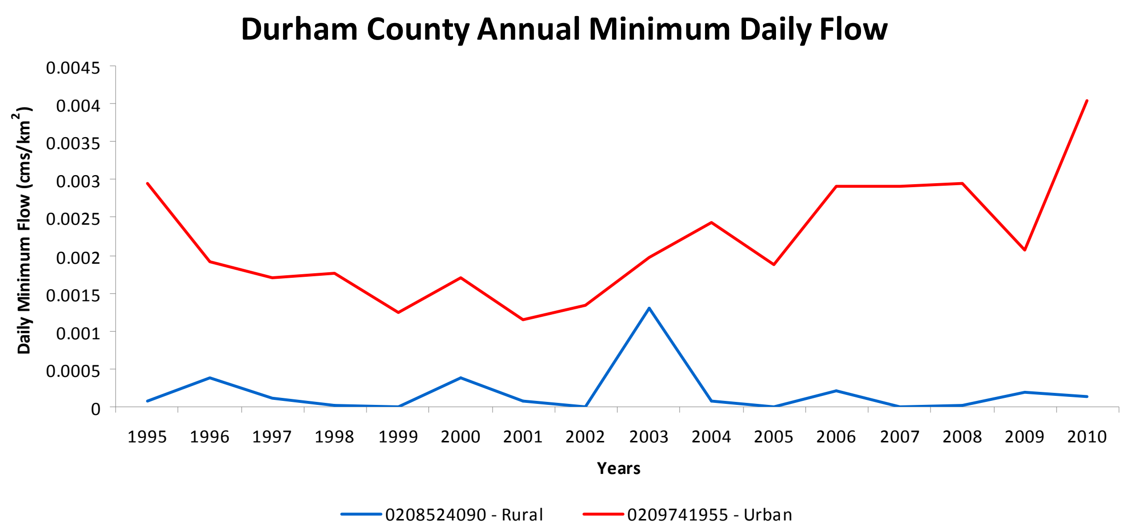
Annual Mean Daily Flow As shown in Figure 29 the urban stream (Northeast Creek, 0209741955) has the highest annual mean daily flow; the rural stream has the lowest (Mountain Creek, 0208524090).

Figure 29. Annual Mean Daily Flow Results for Durham County stations.



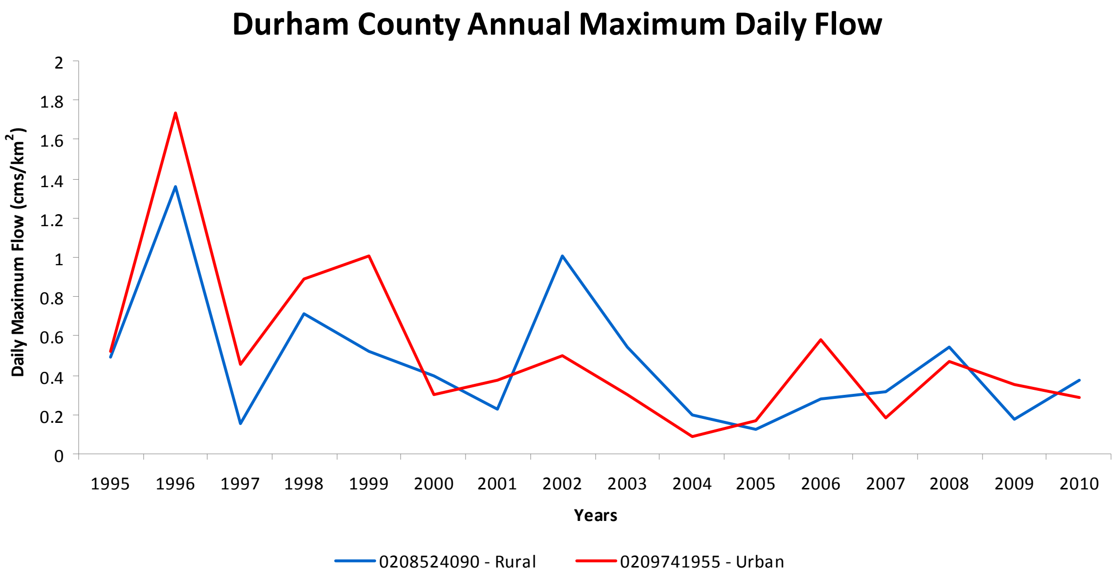
Annual Minimum Daily Flow Figure 30 shows that the urban stream (Northeast Creek, 0209741955), had the highest minimum daily flows. The rural stream (Mountain Creek, 0208524090) had the lower minimum daily flow.

Figure 30. Annual Minimum Daily Flow results for Durham County stations.



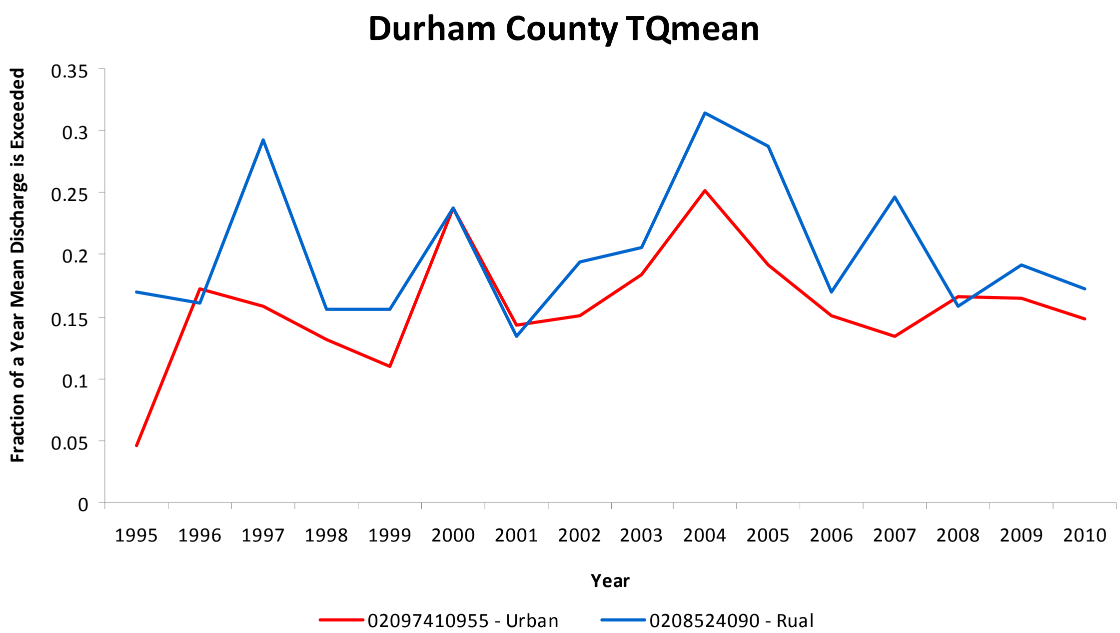
Annual Maximum Daily Flow The time series plots for this metric are shown in Figure 31. In most years, the urban station (Northeast Creek, 0209741955) had the higher annual maximum daily flows than the rural stream (Mountain Creek, 0208524090).

Figure 31. Annual Maximum Daily Flow results for Durham County stations.



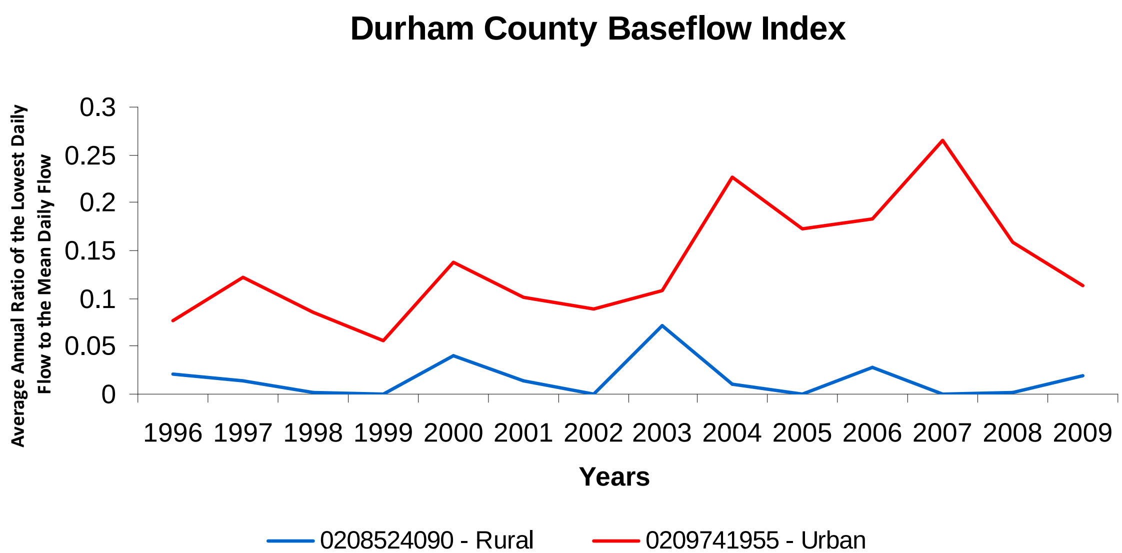
T$_{Qmean}$ The time series plots for this metric are shown in Figure 32. The urban station had lower values than its rural counterpart for most years.

Figure 32. T_{Qmean} results for Durham County stations.



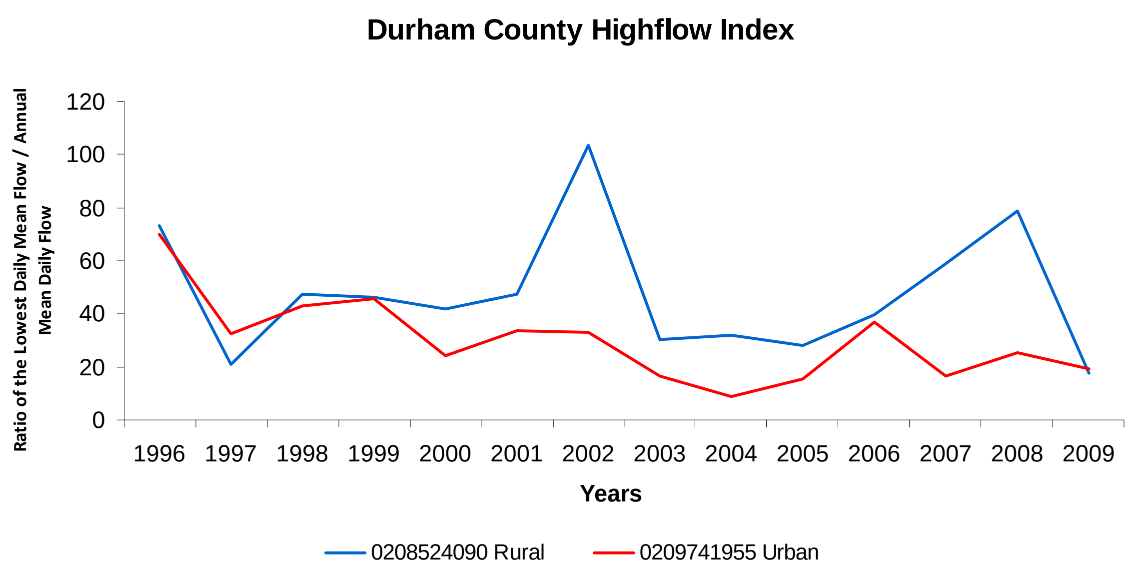
Baseflow Index Figure 33 show the urban stream had higher values of baseflow index than its rural counterpart.

Figure 33. Baseflow Index results for Durham County stations.



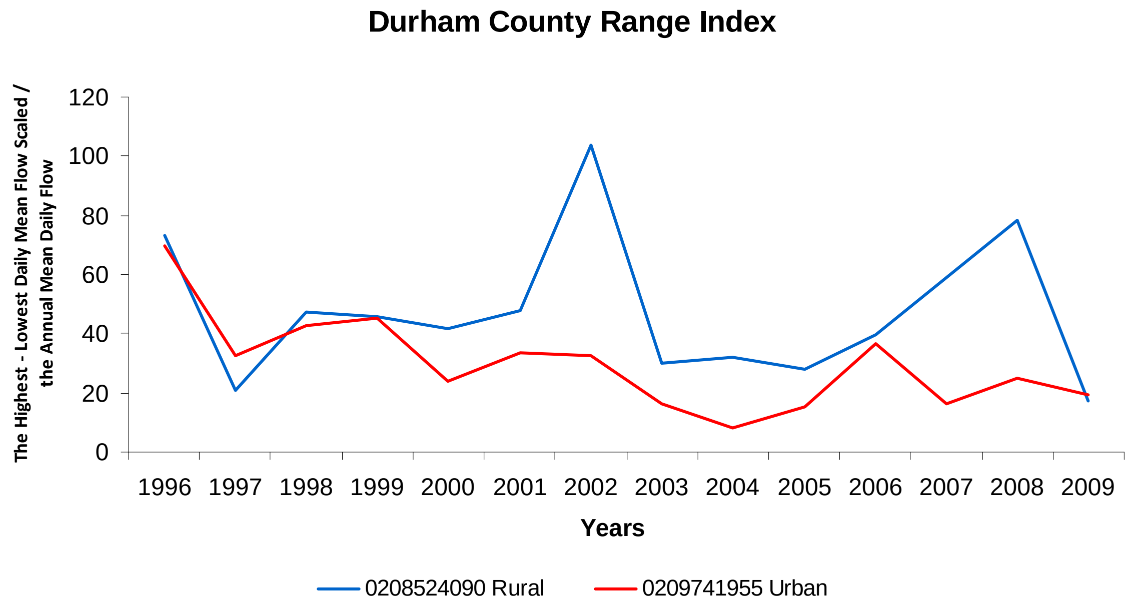
Highflow Index As shown in Figure 34, the rural stream had higher values of highflow index in most years than the rural stream.

Figure 34. Highflow Index results for Durham County stations.



Range Index The pattern of this metric is similar to that of highflow index (Figure 35). That is, the rural stream had higher values in most years than the rural stream.

Figure 35. Range Index results for Durham County stations.



Flow Duration Curve and DAYCV The values for these two metrics are given in Table 16. The rural stream had a higher DAYCV value (395.3) than the rural stream (282.1). The values of (Q10-Q95)/Q50 showed the same pattern. The rural station has a value of 5.98. The urban station has a value of 5.29, respectively.

Table 16. Flow Duration Curve and Coefficient of Variation Results for Durham County.

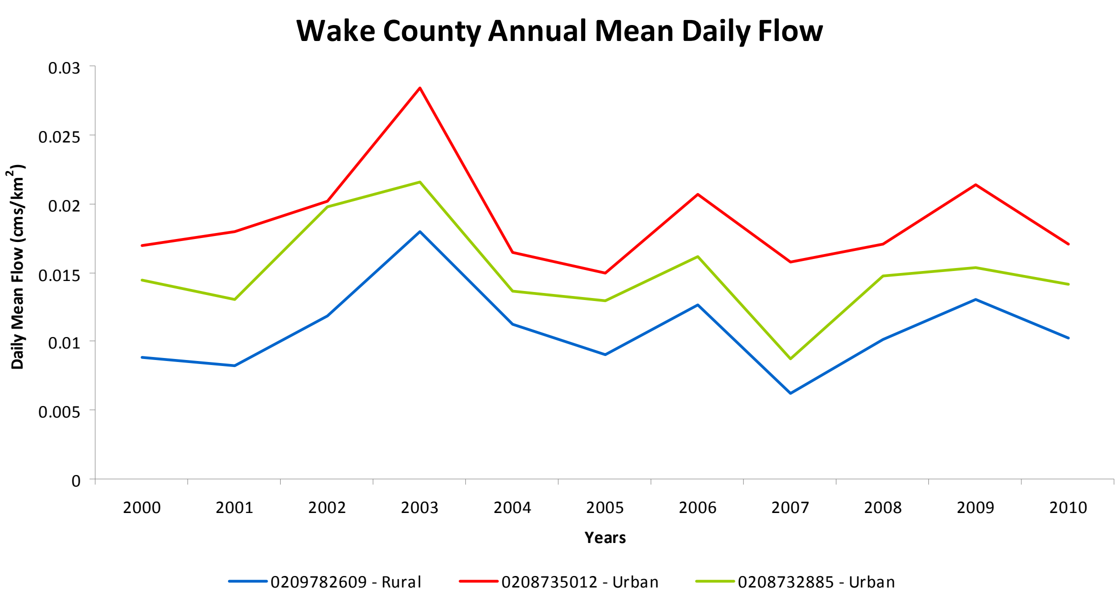
County	Site Number	Region	Urban or Rural	DAYCV	Q10-Q95/Q50
Durham	0209741955	Piedmont	Urban	282.1	5.29
Durham	0208524090	Piedmont	Rural	395.3	5.98

Wake County

Flow data from three stations in this county were analyzed and evaluated.

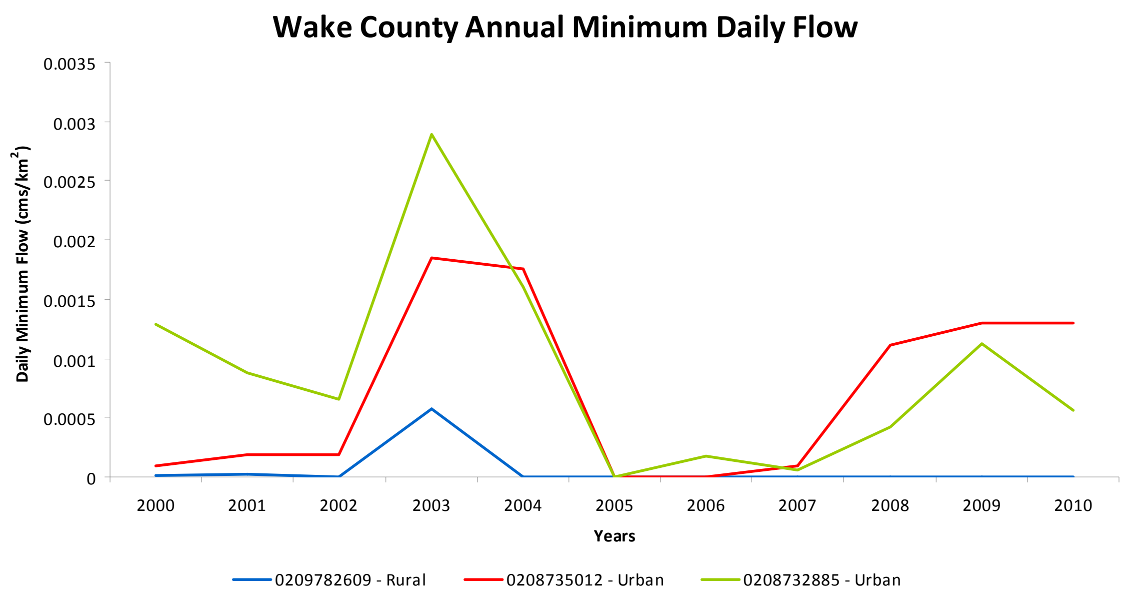
Annual Mean Daily Flow As shown in Figure 36 the two urban streams (Rocky Branch Creek, 0208735012; March Creek, 0208732885) have the highest annual mean daily flow; the rural stream has the lowest (White Oak Creek, 0209782609).

Figure 36. Annual Mean Daily Flow results for Wake County stations



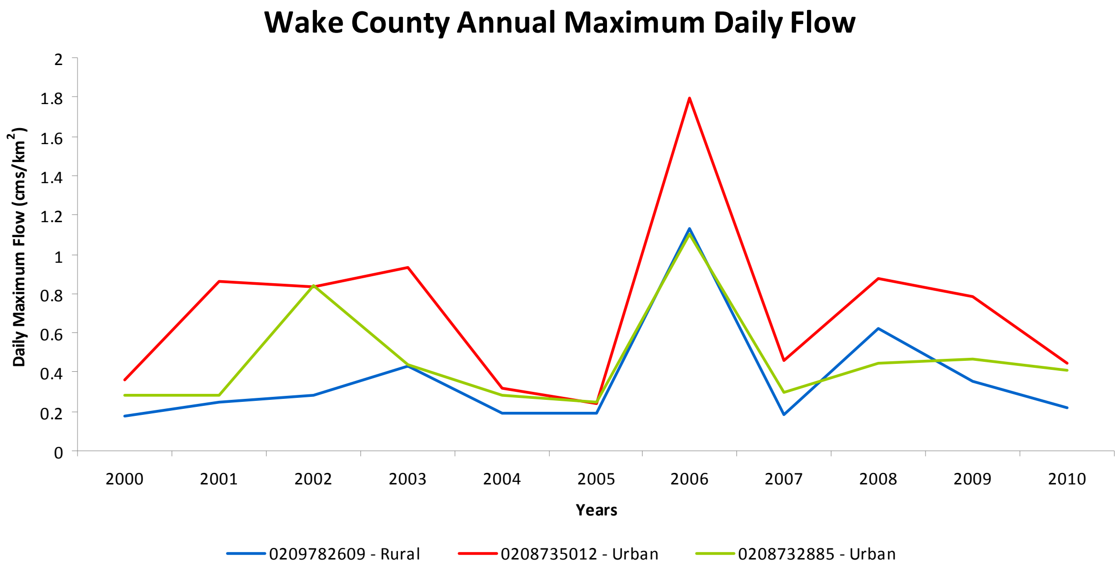
Annual Minimum Daily Flow Figure 37 shows that in most years of the study period, the urban streams (Rocky Branch Creek, 0208735012; March Creek, 0208732885) had the highest minimum daily flows. The rural stream (White Oak Creek, 0209782609) had relatively lower minimum daily flow.

Figure 37. Annual Minimum Daily Flow results for Wake County stations.



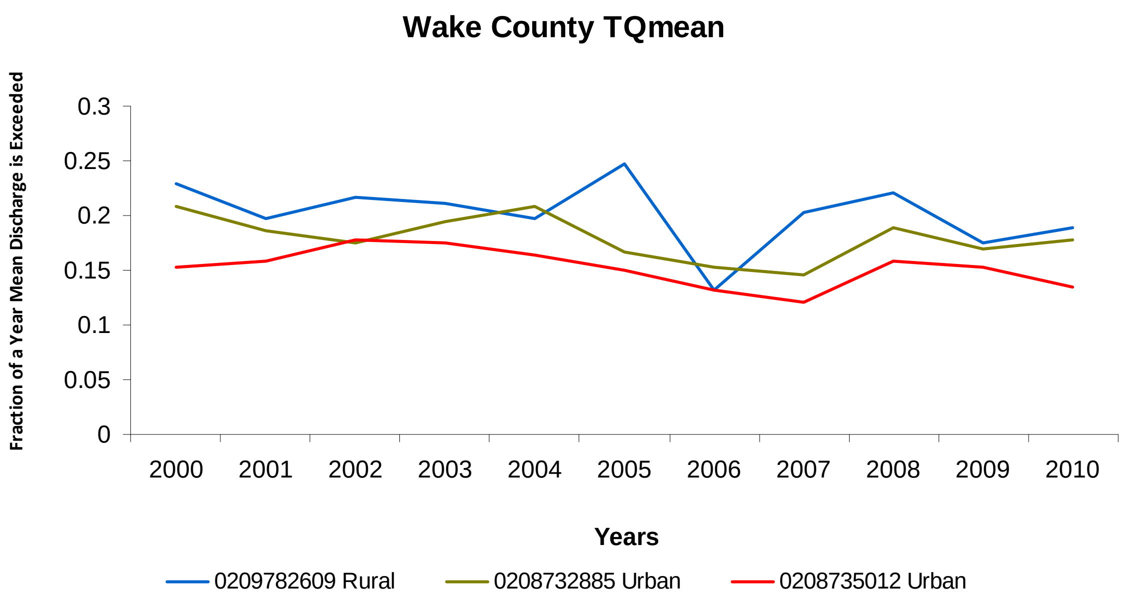
Annual Maximum Daily Flow The time series plots for this metric are shown in Figure 38. The urban stations (Rocky Branch Creek, 0208735012; March Creek, 0208732885) had the higher annual maximum daily flows than the rural stream (White Oak Creek, 0209782609).

Figure 38. Annual Maximum Daily Flow results for Wake County stations.



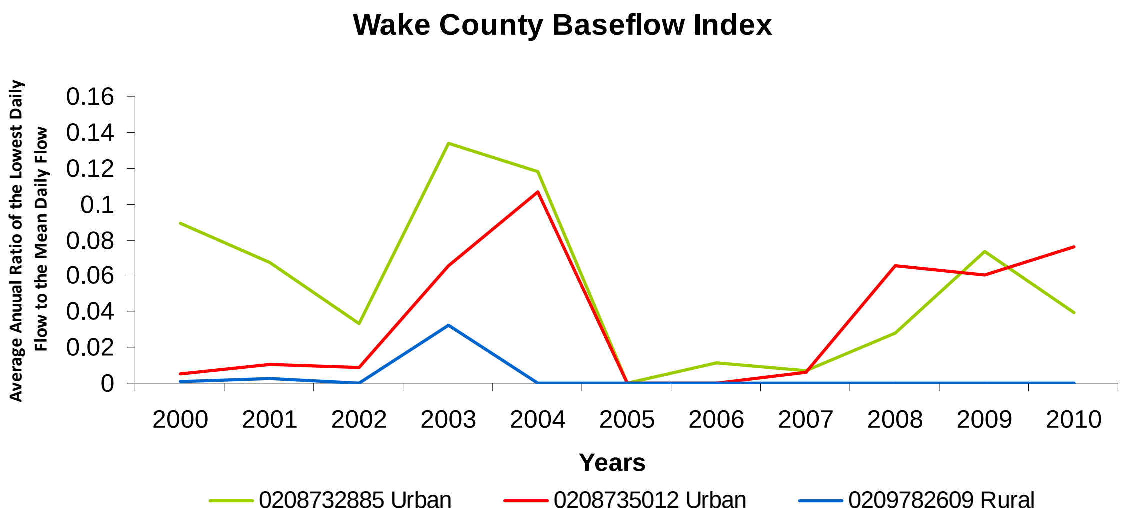
T_{Qmean} The time series plots for this metric are shown in Figure 39. For most of the years the rural station had higher values than its two urban counterparts.

Figure 39. T_{Qmean} results for Wake County stations.



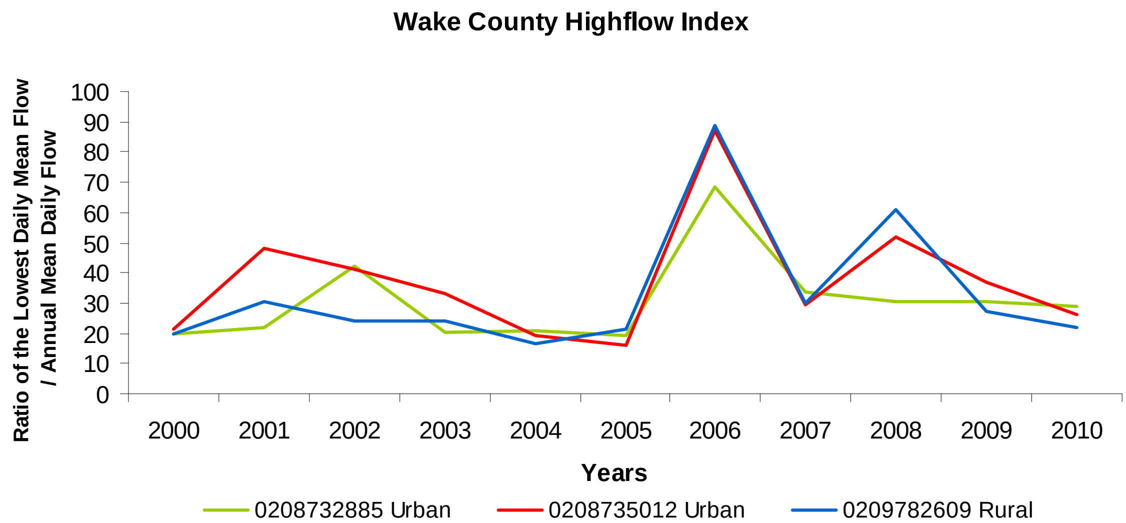
Baseflow Index Figure 40 shows that in most years, the two urban streams had higher values of baseflow index than its rural counterpart.

Figure 40. Baseflow Index results for Wake County stations.



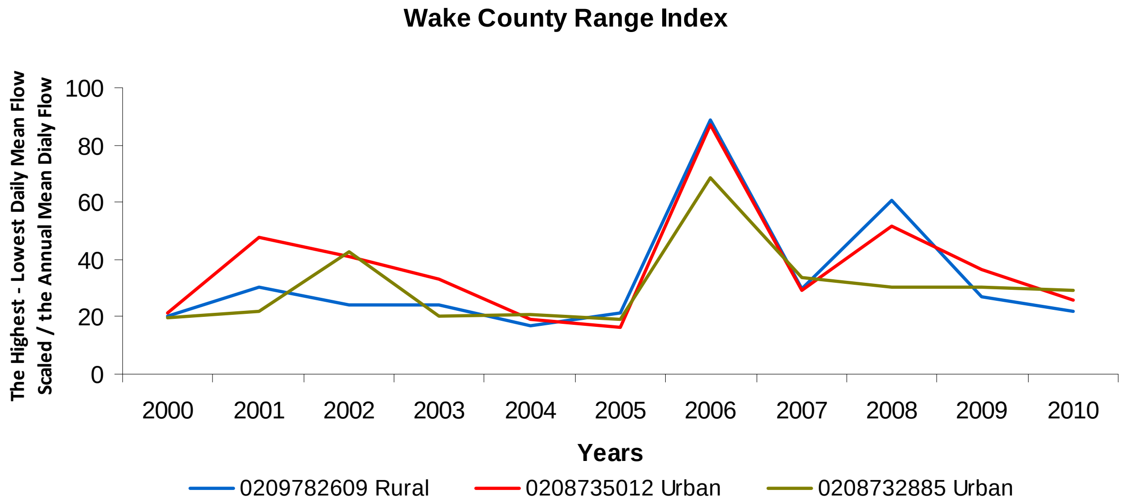
Highflow Index As shown in Figure 41, the urban streams had higher values of highflow index in some years, but lower values in later years compare to the rural stream.

Figure 41. Highflow Index results for Wake County stations.



Range Index The pattern of this metric is similar to that of highflow index (Figure 42). That is, the urban stream had higher values in some years, but lower values in later years than the rural stream.

Figure 42. Range Index results for Wake County stations.



Flow Duration Curve and DAYCV The values for these two metrics are given in Table 17. The rural stream had a higher DAYCV value (317.1) than one urban stream (281.7), but lower than the other urban stream (321.9). The values of (Q10-Q95)/Q50 showed the same pattern. The rural station has a value of 8.57. The two urban stations have a value of 5.20 and 8.94, respectively.

Table 17. Flow Duration Curve and Coefficient of Variation Results for Wake County.

County	Site Number	Region	Urban or Rural	DAYCV	Q10-Q95/Q50
Wake	0208735012	Piedmont	Urban	321.9	8.94
Wake	0208732885	Piedmont	Urban	281.7	5.20
Wake	0209782609	Piedmont	Rural	317.1	8.57

Coastal Plain

Cumberland County

Due to the amount of gaps in the data record for Cumberland County urban stream, DAYCV and the flow duration curve were the only two metrics that could process the streamflow data.

Flow Duration Curve and DAYCV The values for these two metrics are given in Table 18. The urban stream had a higher DAYCV value (106.6) than the rural stream (159.4). The values of (Q10-Q95)/Q50 showed the same pattern. The rural station has a lower value of 2.75. The urban station has a higher value of 2.77, respectively.

Table 18. Flow Duration Curve and Coefficient of Variation Results for Cumberland County.

County	Site Number	Region	Urban or Rural	DAYCV	Q10-Q95/Q50
Cumberland	02104387	Coastal	Urban	159.4	2.77
Cumberland	02103000	Coastal	Rural	106.6	2.75

CHAPTER V

DISCUSSION AND CONCLUSIONS

The focus of this research has one main objective: To use a variety of streamflow metrics to compare the influences of urbanization to rural streams in the different physiographic regions of North Carolina. The metrics used include: Annual mean, maximum, and minimum daily flow, T_{Qmean}, Coefficient of Variation, Baseflow Index, Highlfow Inex, Range Index, and Flow Duration Curve.

The metrics used in this study were chosen with the intention of seeing a pattern develop within the counties and across the different physiographic regions. Many of the comparisons of the metrics between the urban and rural streams did not reveal the patterns that were anticipated (Table 19).

Table 19. Results for all Metric for each Region.

Metric	Expected Values of the Urban Metric	Bunc. County Urban	Meck. County Urban	Guilford County Urban	Durham County Urban	Wake County Urban	Cumb. County Urban
Annual Mean Daily Flow	High	Low	High	High	High	High	N/A
Annual Maximum Daily Flow	High	Unclear	High	Low	High	High	N/A
Annual Minimum Daily Flow	High	Low	Unclear	High	Unclear	High	N/A
TQmean	Low	Unclear	High	Low	Low	Low	N/A
Coefficient of Variation	High	Unclear	Low	High	Low	Unclear	High
Baseflow Index	Low	High	High	Low	High	High	N/A
Highflow Index	High	Unclear	Low	Unclear	Low	Unclear	N/A
Range Index	High	Unclear	Low	Unclear	Low	Unclear	N/A
Flow Duration Curve	High	Unclear	Unclear	High	Low	Unclear	High

The objective was hindered by gaps in the data and lack of stream stations in urbanized areas for the Mountain and Coastal Plain. Overall, the Piedmont sites showed the best results between the rural and urban streams and the predicted outcome as compared to the Coastal and mountain sites. The Piedmont showed the best results for annual mean daily flow, annual maximum daily flow (with the exception of Guilford County where the rural stream has the higher value), and T_{Qmean} (with the exception of Mecklenburg County where the urban stream had a higher value). For the remaining metrics, annual minimum daily flow, coefficient of variation, baseflow index, highflow index, range index, and flow duration curve all had mixed results with no consistence.

Due to gaps in the data, only two metrics could be processed for the Cumberland urban station, coefficient of variation and flow duration curve. The results showed that both urban streams had the higher values for both metrics. Part of this may have resulted from the rural watershed being very large with most of it possibly being in the Piedmont. This may have resulted in a possible skewed rural value for the results of this region.

The metrics for the mountain region showed a much different outcome with none of the expected results. The results of the mountain sites may be attributed to the definition of an urban watershed for the mountain region and the size of the urban watershed. The impervious area for that region was significantly less than the other regions and therefore the threshold may not have been met for the metric to have adequate results.

With such a large watershed, for the urban stream in Buncombe County, the results may have been counter-intuitive. The urban stream had such a large watershed that any flood events would have a gently rounded hydrograph and a more drawn out peak for long duration. This is because water can be stored on the floodplain and in the channel in greater volumes; compared to the rural and smaller watersheds which would have a sharper, higher peak and a shorter duration hydrograph because water is not stored effectively in the smaller watersheds. Thus, any metric based on flow ranges or extremes would become less sensitive to urbanization as watershed size increases. This could be the case for any large watershed used in this study. Topography in that region is also markedly steeper which may have an impact on the outcome of the study. These factors should be considered when evaluating future research on the relationship between the percentage of impervious surface area and the effectiveness of some flow metrics.

The metrics used for this study, for the most part, appeared to be effective, especially for the Piedmont sites. The Mountain and Coastal Plain sites outcome was much different. Future studies should focus on re-evaluating the watershed size and definition of the impervious surfaces that are present in the mountain regions. Other mountainous areas with larger populations and urban characteristics should be examined to allow for a better comparison to the Piedmont, Mountain, and Coastal areas. Future research would benefit from evaluating areas outside of North Carolina that have similar physiographic characteristics so that site selection would be less limited and would ultimately have better data sets available for study.

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